

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

---

USDA Forest Service / UNL Faculty Publications U.S. Department of Agriculture: Forest Service --  
National Agroforestry Center

---

9-2013

## Climate Change and North American Rangelands: Assessment of Mitigation and Adaptation Strategies

Linda A. Joyce  
*USDA Forest Service, ljoyce@fs.fed.us*

David D. Briske  
*Texas A&M University*

Joel R. Brown  
*New Mexico State University*

H. Wayne Polley  
*USDA-ARS, wayne.polley@ars.usda.gov*

Bruce A. McCarl  
*Texas A&M University*

*See next page for additional authors*

Follow this and additional works at: <https://digitalcommons.unl.edu/usdafsfacpub>



Part of the [Forest Biology Commons](#), [Forest Management Commons](#), [Other Forestry and Forest Sciences Commons](#), and the [Plant Sciences Commons](#)

---

Joyce, Linda A.; Briske, David D.; Brown, Joel R.; Polley, H. Wayne; McCarl, Bruce A.; and Bailey, Derek W., "Climate Change and North American Rangelands: Assessment of Mitigation and Adaptation Strategies" (2013). *USDA Forest Service / UNL Faculty Publications*. 347.  
<https://digitalcommons.unl.edu/usdafsfacpub/347>

This Article is brought to you for free and open access by the U.S. Department of Agriculture: Forest Service -- National Agroforestry Center at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in USDA Forest Service / UNL Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

---

**Authors**

Linda A. Joyce, David D. Briske, Joel R. Brown, H. Wayne Polley, Bruce A. McCarl, and Derek W. Bailey

## Invited Synthesis

# Climate Change and North American Rangelands: Assessment of Mitigation and Adaptation Strategies

Linda A. Joyce,<sup>1</sup> David D. Briske,<sup>2</sup> Joel R. Brown,<sup>3</sup> H. Wayne Polley,<sup>4</sup> Bruce A. McCarl,<sup>5</sup> and Derek W. Bailey<sup>6</sup>

Authors are <sup>1</sup>Quantitative Ecologist, Human Dimensions Research Program, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO 80526, USA; <sup>2</sup>Professor, Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843, USA; <sup>3</sup>Rangeland Management Specialist, USDA-NRCS Jornada Experimental Range, New Mexico State University, Las Cruces, NM 88003, USA; <sup>4</sup>Research Ecologist, USDA-ARS Grassland, Soil and Water Research Laboratory, Temple, TX 76502, USA; <sup>5</sup>Distinguished Professor, Department of Agricultural Economics, Texas A&M University, College Station, TX 77843, USA; and <sup>6</sup>Professor, Animal and Range Sciences Department, New Mexico State University, Las Cruces, NM 88003, USA.

### Abstract

Recent climatic trends and climate model projections indicate that climate change will modify rangeland ecosystem functions and the services and livelihoods that they provision. Recent history has demonstrated that climatic variability has a strong influence on both ecological and social components of rangeland systems and that these systems possess substantial capacity to adapt to climatic variability. Specific objectives of this synthesis are to: 1) evaluate options to mitigate greenhouse gas emissions and future climate change; 2) survey actions that individuals, enterprises, and social organizations can use to adapt to climate change; and 3) assess options for system transformation when adaptation is no longer sufficient to contend with climate change. Mitigation for carbon sequestration does not appear economically viable, given the small and highly variable carbon dioxide fluxes of rangeland ecosystems and the high transaction costs that would be incurred. In contrast, adaptation strategies are numerous and provide a means to manage risks associated with climate change. Adaptation strategies are diverse, including altered risk perception by individuals, greater flexibility of production enterprises, and modifications to social organizations that emphasize climatic variability, rather than consistency. Many adaptations represent “no regrets” actions because their implementation can be justified without emphasis on pending climate change. Adaptations specific to livestock production systems can include flexible herd management, alternative livestock breeds or species, innovative pest management, modified enterprise structures, and geographic relocation. Social-ecological systems in which adaptation is insufficient to counter the adverse consequences of climate change might undergo transformative change to produce alternative ecosystem services, production enterprises, and livelihoods. The rangeland profession is in a pivotal position to provide leadership on this global challenge because it represents the intersection of management and scientific knowledge, includes diverse stakeholders who derive their livelihoods from rangelands, and interacts with organizations responsible for rangeland stewardship.

**Key Words:** carbon sequestration, land change science, social-ecological systems, social learning, sustainability, transformation

### INTRODUCTION

Climate change science has detected measurable shifts to long-term climatic trends in combination with greater climatic variability, and both are projected to continue in the future. These changes in climate, often referred to as the “greenhouse effect,” are a consequence of increasing atmospheric concentrations of greenhouse gases (GHG), including carbon dioxide (CO<sub>2</sub>), that have contributed to a global temperature increase of approximately 1°C since industrialization (ca. 1750). Temperatures are anticipated to increase by as much as 2°C

by midcentury, with the greatest warming at high latitudes (IPCC 2007a; Karl et al. 2009; NRC 2010). A warming atmosphere is projected to modify both mean annual precipitation and its variability, and increasing atmospheric energy is anticipated to amplify the frequency and intensity of severe weather events (IPCC 2007a, 2012; NRC 2010). The current projections indicate that the southwest and southern plains of the United States and northern Mexico will become warmer and drier, the Great Basin will experience warmer drier summers and reduced snowpack in winter, and the northern United States and southern Canada will become warmer and wetter. These climate changes have a high probability of substantially modifying the current function of ecosystems, and the services and livelihoods that they provision (see companion article in this issue, Polley et al. 2013). The indirect effects of climate change on fire regimes, and population densities and ranges of insects, invasive species, plant and animal diseases, and parasites are likely to rival those of direct climate change drivers (MEA 2005; NRC 2010).

This article was commissioned by the board of directors of the Society for Range Management in support of the society's position on climate change.

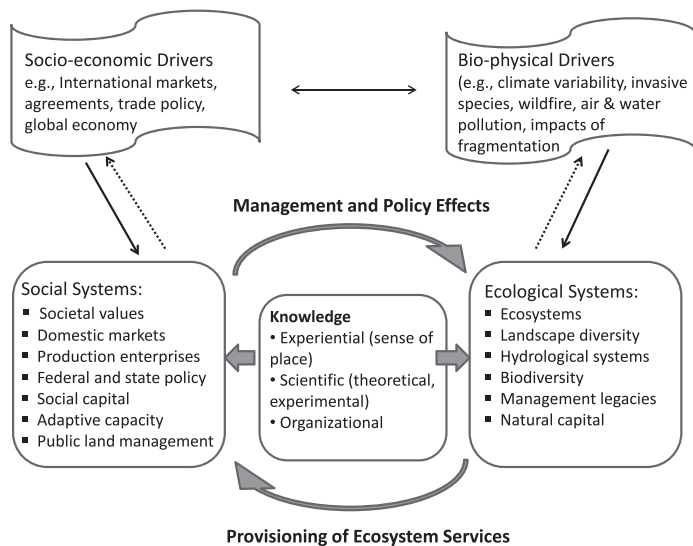
The alternate editor-in-chief, M. K. Owens, was responsible for the editorial handling of this manuscript.

Correspondence: Linda A. Joyce, USDA Forest Service Rocky Mountain Research Station, 240 West Prospect, Fort Collins, CO 80526, USA. Email: ljoyce@fs.fed.us

Manuscript received 25 September 2012; manuscript accepted 3 June 2013.

© 2013 The Society for Range Management

This document is a U.S. government work and is not subject to copyright in the United States.



**Figure 1.** Conceptual depiction of the interactive relationships within the rangeland social-ecological system as influenced by the experiential knowledge, scientific knowledge, and organizational knowledge and the socio-economic and bio-physical drivers (modified from Reynolds and Stafford Smith 2002).

Rangeland systems consist of interacting ecological and social components that are influenced by bio-physical drivers, such as climate, and socio-economic drivers, such as international markets (Fig. 1; Reynolds and Stafford Smith 2002; Reynolds et al. 2007; Fox et al. 2009). Human activities, through management, facilitate the provisioning of ecosystem services from social-ecological systems (Table 1), and can fundamentally alter local social-ecological interactions (Stafford Smith et al. 2007). Markets, private and nongovernmental institutions, and governmental economic and environmental policy also affect management actions and the provisioning of ecosystem services (Fig. 1). In the case of climate change, humans can implement actions to both minimize the severity of climate change by reducing GHG emissions and minimize the detrimental effects of these changes on social-ecological systems by implementing various management and policy decisions. Consequently, strategies for navigating climate change should be developed in the context of the entire social-ecological system.

A unique characteristic of social-ecological systems is the capacity to “learn” from both positive and negative outcomes to previous natural events and management actions (Gunder-son et al. 2006). Lessons learned from the drought of the 1930s resulted in regional and national institutional change, fostered learning at the enterprise level, and initiated research on soil conservation. Climate change will alter the environmental and economic risks within rangeland systems (Fig. 1); human perceptions and behaviors play a significant role in risk assessment and the capacity to adapt to change (Knapp and Fernandez-Gimenez 2009; Briske et al. 2011; D’Odorico et al. 2013). As with the 1930s drought, the development of management actions for mitigation and adaptation will depend on the timely integration of local experiential knowledge with scientific and organizational knowledge on climate change impacts and ecological responses. Enhancing adaptive capacity

**Table 1.** Glossary of terms used to address strategies for responding to climate change in social-ecological systems.

<b>Adaptation:</b> social, economic, or cultural adjustment to a change in the physical or social environment of a system (Chapin et al. 2009)
<b>Anticipatory adaptation:</b> adaptation that takes place before impacts of climate change are observed (IPCC 2007a, WGII Glossary)
<b>Autonomous adaptation:</b> adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems (IPCC 2007a, WGII Glossary)
<b>Planned adaptation:</b> adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state (IPCC 2007a, WGII Glossary)
<b>Adaptive capacity:</b> capacity of social-ecological systems, including both their human and ecological components, to respond to, create, and shape change in the system (Chapin et al. 2009)
<b>Carbon sequestration:</b> capture and storage of atmospheric CO <sub>2</sub> produced in the global energy system, most often in soils and vegetation of terrestrial systems (Follett et al. 2001)
<b>Ecosystem services:</b> benefits that humans receive from ecosystems (MEA 2005)
<b>Human well-being:</b> quality of life in terms of material needs, freedom and choice, good social relations, and personal security (Chapin et al. 2009)
<b>Mitigation:</b> human actions to reduce the magnitude of greenhouse gasses (GHG) emissions into the atmosphere and to sequester existing atmospheric CO <sub>2</sub> as a means to reduce the impact of climate change
<b>Resilience:</b> the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks (Walker et al. 2004)
<b>Social-ecological system:</b> system with interacting and interdependent physical, biological, and social components, emphasizing the perspective of humans in nature (Chapin et al. 2009)
<b>Transformation:</b> fundamental change in social-ecological systems that results in the formation of novel state variables and feedbacks, ecosystem services, and livelihoods when existing conditions make the current system untenable (Walker et al. 2004; Chapin et al. 2009)
<b>Vulnerability:</b> risk to the adaptive capacity of systems or the potential harm caused to systems when this capacity has been exceeded (NRC 2010); degree to which a system is likely to experience harm owing to exposure and sensitivity to a specified hazard or stress and its adaptive capacity to respond to that stress (Chapin et al. 2009)

and facilitating social learning across multiple social-ecological levels is a critical component of confronting climate change on rangelands (Nelson et al. 2007; Pelling 2011).

Three broad strategies exist to address the social-ecological consequences of climate change: 1) *mitigation* by adjusting management practices, enterprises, and policies to increase carbon (C) sequestration and reduce GHG emissions, thereby lessening the future extent of climate change, 2) *adaptation* by modifying management practices, enterprises, and social systems to minimize negative consequences and exploit opportunities of climate change, and 3) *transformation* by shifting to alternative enterprises and ecosystems services and modifying human expectations of the function, behavior, and value of the services provided by future rangeland systems. Transformation is required when irreversible change in social

or ecological conditions exceeds the adaptive capacity of the current system.

The overarching goal of this synthesis is to expand upon these strategies and associated actions, within a framework of social-ecological systems. We emphasize the adaptive capacity and social learning necessary to maintain the provision of ecosystem services and to sustain enterprise viability and human livelihoods in response to accelerating climate change. Specific objectives are to: 1) evaluate options to mitigate GHG emissions and future climate change, 2) survey actions that individuals, enterprises, and social organizations can use to adapt to climate change, and 3) assess options for transformational change when adaptation is no longer sufficient to contend with climate change. Livestock production systems are emphasized because they represent a major source of human livelihoods on rangelands.

## MITIGATION TO LESSEN FUTURE CLIMATE CHANGE

Climate change mitigation refers to a broad set of actions intended to reduce the rate and extent of climate change by decreasing GHG concentrations in the atmosphere (IPCC 2007b). Mitigation includes both reducing GHG emissions and increasing C sinks primarily in soils and vegetation. Rangeland management can influence the flux of GHGs between land and atmosphere sufficiently to alter atmospheric GHG concentrations over decadal timeframes, but it is unlikely to be a major contributor to mitigation. Pacala and Socolow (2004) estimated that forestry and agricultural soil management have the potential to achieve  $\sim 15\%$  of an overall GHG management strategy to stabilize climate over the next 50 yr. Current knowledge of C fluxes in rangeland systems indicates that policies and programs should focus on long-term strategies to protect existing C pools, rather than attempt to enhance future sequestration (Booker et al. 2013).

Rangeland management, including livestock production, influences fluxes of the three dominant GHGs: methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and  $\text{CO}_2$  between land and atmosphere. These gases have different potentials for trapping thermal radiation emitted from Earth and, therefore, uniquely contribute to global warming. The relative contributions of these gases to warming are typically calculated using the 100-yr *global warming potential* (GWP) and are often expressed in *CO<sub>2</sub> equivalents* ( $\text{CO}_2\text{e}$ ), the amount of  $\text{CO}_2$  required to match the GWP of a given amount of  $\text{CH}_4$  or  $\text{N}_2\text{O}$  (IPCC 2001). For example, the relative contribution of one ton of  $\text{N}_2\text{O}$  to global warming is equivalent to 310 tons of  $\text{CO}_2$ ; one kg of  $\text{CH}_4$  has the warming equivalent ( $\text{CO}_2\text{e}$ ) of 21 kg of  $\text{CO}_2$  (US EPA 2012; also, see Supplemental Materials; available online at <http://dx.doi.org/10.2111/REM-D-12-00142.s1>). The net emissions of GHG in mitigation strategies are usually converted to this metric of  $\text{CO}_2$  equivalents ( $\text{CO}_2\text{e}$ ) for reporting and trading purposes (US EPA 2012).

Emissions of GHGs from rangeland management activities are small per unit area and highly variable, but not inconsequential in the context of global emissions. Rangeland ecosystems can function as either sources or sinks for  $\text{CO}_2$  depending largely upon resource availability, primarily soil

water content (Polley et al. 2013 [this issue]). Ruminant livestock production is estimated to account for  $> 30\%$  of the total 6 875 M  $\text{CO}_2\text{e}$  of  $\text{CH}_4$  emissions on a global basis through enteric fermentation and manure management, with about 18% of the total due to livestock grazing on rangelands (Smith et al. 2007). In the United States, total methane emissions are estimated at 686 MMg  $\text{CO}_2\text{e}$ , with about 20% attributed to enteric fermentation and 7% to manure management (US EPA 2012). Although there are no systematic assessments separating rangelands and intensively managed pastures, most estimates place rangeland livestock grazing at less than one-half of the total (Liebeg et al. 2010). The manure management component is attributable entirely to confined livestock, and there is little opportunity for emission reductions in extensively managed rangeland systems. Rangeland vegetation and soils can be either sinks or sources of  $\text{CH}_4$ , but these fluxes are considered to be small relative to direct emissions from livestock (Liebig et al. 2010). Emissions of  $\text{N}_2\text{O}$  from unfertilized rangelands are variable and difficult to quantify, but are estimated to account for  $< 1\%$  of agricultural emissions in the United States and worldwide (US EPA 2012).

### Mitigation Strategies

Mitigation strategies involve modifications to the management and structure of production enterprises to increase or maintain the amount of sequestered C and decrease emissions of GHGs into the atmosphere (for possible strategies, see Table 2). Regulations and policies, if properly developed, could incentivize enterprise-level activities to address mitigation in land management.

**C Sequestration Potential.** Most credible estimates place the effective potential of rangeland C sequestration at about one-half that of US croplands (130–300 vs. 270–700 MMg  $\text{CO}_2\text{e}$  for rangeland and cropland respectively; Lal et al. 1998; Follett et al. 2001). Although the potential for C sequestration on rangelands is relatively low per unit of land area, the vast land area of rangelands and strong positive correlation between C sequestration and other desired ecosystem services makes this a viable mitigation strategy (Follett et al. 2001). These C sequestration estimates include conversion of cropland to rangeland and restoration of degraded rangelands ( $64\text{--}167 \text{ MMg } \text{CO}_2\text{e} \cdot \text{y}^{-1}$ ), and improved management on existing rangelands ( $20\text{--}59 \text{ MMg } \text{CO}_2\text{e} \cdot \text{y}^{-1}$ ). As these values indicate, the potential impact of rangeland C sequestration accounts for approximately 2.5% and  $< 1\%$  of, respectively, total US  $\text{CO}_2\text{e}$  emissions in 2010 (6 800 MMg  $\text{CO}_2\text{e}$ , US EPA 2012).

The amount of C sequestered in rangeland ecosystems is a direct consequence of photosynthetic C inputs relative to C losses from soils by plant and soil microbial respiration. Grazing at recommended stocking rates has a relatively minor impact on the production:loss ratio and, therefore, on soil C pools (Derner et al. 2006; Derner and Schuman 2007; Polley et al. 2008). In some rangeland ecosystems, grazing can stimulate root production in upper soil layers by modifying species composition to shallow-rooted species, resulting in increased soil C at this location, but not throughout the entire profile (Schuman et al. 1999; Derner et al. 2006). However, intensive, chronic grazing can reduce belowground primary production (Milchunas and Lauenroth 1993) and C inputs (Schuman et al.



**Table 2.** Potential mitigation actions to sequester carbon and reduce greenhouse gasses (GHG) emissions arranged within broad categories of enterprise and social institutions. Mitigation strategies will need to consider all GHGs and be tailored to specific consequences of climate change in various geographic regions.

Mitigation category <sup>1</sup>	Description <sup>1</sup>	Citations
<b>Enterprise</b>		
Maintain/improve forage quality	Reduce CH <sub>4</sub> emissions from livestock	Craine et al. 2010
Livestock supplementation	Improve efficiency of livestock production and reduce CH <sub>4</sub> emissions by providing supplemental nitrogen, lipids, and ionophores	Johnson and Johnson 1995; Guan et al. 2006
Limit intensive forage production	Reduce management inputs and emissions	Tilman et al. 2002
Conservative stocking	Increase C sequestration by increasing belowground organic C	Follett et al. 2001
Restore degraded systems	Optimize C sequestration by increasing belowground organic C	Follett et al. 2001
Tolerate woodland expansion	Increase C sequestration, but also NO emissions	Archer et al. 2001
Add legumes on rangeland	Reduce N <sub>2</sub> O emissions	US EPA 2012
Reduce herd size	Reduces emissions from feed production and animal and manure CH <sub>4</sub> /N <sub>2</sub> O	McCarl and Schneider 2000
Reduce N fertilization	Reduce N <sub>2</sub> O emissions	Liebig et al. 2010
<b>Social institutions</b>		
Land use policies	Maintain CRP, convert cropland to rangeland	Follett et al. 2001
Eliminate perverse incentives	Modify drought and other relief programs to reward anticipatory management	Thurrow and Taylor 1999
Facilitate adaptive management	Promote collaborative management and monitoring programs, and management-science partnerships	Chapin et al. 2010; Fazey et al. 2010
Develop social learning networks	Develop web-based media to share tools and relevant information	Stafford Smith et al. 2007, 2011
Reduce institutional mismatches with resources	Long-term planning horizons, promote local and regional actions rather than national programs, increase management flexibility	Chapin et al. 2010

<sup>1</sup>CH<sub>4</sub> indicates methane; C, carbon; NO, nitric oxide; N<sub>2</sub>O, nitrous oxide; N, nitrogen; CRP, conservation reserve program.

2001). Other disturbances that affect only aboveground biomass, such as fire, typically have a limited effect on soil C pools as long as adequate plant cover is maintained and soil is not disturbed (Dai et al. 2006; Cleary et al. 2010; Rau et al. 2010). For example, burning tallgrass prairie stimulated leaf area and canopy photosynthesis, although these C gains were offset by increased respiration from both the soil and vegetation (Bremer and Ham 2010).

Woody plant encroachment of grasslands often increases soil pools of organic C and total nitrogen (Archer et al. 2001; Asner et al. 2004; Briggs et al. 2005; Hughes et al. 2006), but the results are not entirely consistent (Jackson et al. 2002; McCarron et al. 2003). In addition, potential tradeoffs can occur among specific GHGs in response to natural events or management actions. For example, an increase in C sequestration associated with woody plant encroachment was also associated with an increase in emissions of nitric oxide gas and nonmethane hydrocarbons (Archer et al. 2001). Grassland encroachment by *Prosopis glandulosa* var. *glandulosa* increased nitrogen (N) oxide fluxes by greater than 20-fold during periods of nitrification of soil N in northern Texas (Martin et al. 2003). The magnitude of these emissions was positively correlated with aboveground biomass and both temperature and precipitation.

**Potential to Reduce GHG Emissions.** Management strategies can reduce GHG emissions (Table 2), but it is difficult to generalize about management effects on net GHG emissions because specific GHGs at specific locations show varied responses to management. For example, an increase in N<sub>2</sub>O emissions following N fertilization can offset benefits derived from an increase in soil C sequestration that results from increased plant

production (Liebig et al. 2010). N fertilization is an infrequent practice on native rangelands, but it must be accounted for in enterprise inventories when improved pastures or crop residues are part of production systems. Methane emissions from livestock negated approximately 33% of C sequestration in crested wheatgrass pastures and heavily grazed grassland, but only 12% of C sequestration in moderately grazed native grasslands. Collectively, results from a mixed grass prairie of the Northern Plains indicate that moderate grazing is most effective in achieving net reductions in total GHG emissions at the enterprise level (Liebig et al. 2010).

Reducing fossil-fuel-derived inputs to livestock production systems also can reduce GHG emissions (Zilverberg et al. 2011). Replacing hay with unfertilized dormant forage and crude protein supplementation can significantly reduce energy inputs and net C emissions per unit of livestock production, especially in northern systems in which the production of winter feed constitutes a large fraction of total energy usage, and in systems in which large fertilizer inputs are used to produce fodder crops. Energy used to produce winter feed ranged from 0 to 46% of the total fossil fuel energy requirement among the cow-calf production systems studied by Zilverberg et al. (2011).

Realizing the full potential of rangelands to sequester C (130–300 MMg CO<sub>2</sub>e) could offset ~2–4% of total US emissions. This potential offset would be effective for a limited period as a new equilibrium is reached in C sequestration in the soil, likely in 10–30 yr (West and Six 2007). The ability to cost-effectively reduce enteric CH<sub>4</sub> emissions in extensive grazing systems via improved grazing management, feed supplements and genetic improvement is generally estimated to be limited to 20% of the rangelands total (<15 MMg CO<sub>2</sub>e·y<sup>-1</sup>). US

rangeland livestock production systems are comparatively efficiently managed (based on stocking rate, calving efficiency, diet quality) overall, limiting the opportunities for reducing CH<sub>4</sub> and CO<sub>2</sub> emissions or increasing C storage through improved management of existing production systems alone (Liebig et al. 2010). Although N<sub>2</sub>O fluxes can be altered by burning rangeland vegetation, the changes are relatively small compared to other sources and likely are below measurement thresholds in national and regional accounting systems (US EPA 2012).

### Emissions Markets and Mitigation Incentives

Rangeland management practices have been allowed in various carbon marketing schemes designed to reduce GHG emissions. For example, the now defunct Chicago Climate Exchange (2009) protocol allowed enrollment of lands that were not fertilized or irrigated under certain conditions; requirements included a forward-looking plan with a minimum 5-yr commitment to manage for increased soil C storage through practices that include grazing, a sustainable forage-animal balance, and a contingency plan for drought management. Provisions are currently emerging for a grassland burning protocol for rangelands under the Australian Carbon Farming initiative (Australian Government Department of Climate Change and Energy Efficiency, Carbon Farming Initiative 2013).

The inclusion of rangeland management practices in a GHG offset market or in a direct payment for mitigating practices scheme would provide the financial incentive to encourage mitigation strategies. However, a number of issues must be addressed in order to implement such approaches (see Supplemental Materials); consequently, implementation of a US national C market does not appear imminent. Among these issues is the need to accurately estimate changes in soil C in response to management. Terrestrial C sinks in all ecosystems, and on rangelands in particular, are widely dispersed and highly variable in space and among seasons and years, largely because of temporal variation in water availability (Brown et al. 2010; Booker et al. 2013). This inherent spatial and temporal variability, along with the limits of current technologies to estimate soil C content and detect the success of sequestration practices, likely will preclude the use of direct measurement of C sinks as a basis for market transactions. As an alternative, predictive models could be used to assess the value of individual mitigation strategies and develop realistic policy alternatives at larger scales (Lokupitiya and Paustian 2006). Unfortunately, models currently applied to agricultural systems perform poorly in predicting soil C changes and emission fluxes on arid lands in general, and rangelands in particular (Martens et al. 2005; Brown et al. 2010).

Potential sequestration rates on US rangelands range from <0.1 to nearly 1.0 Mg CO<sub>2</sub>e · ha<sup>-1</sup> · yr<sup>-1</sup> over an extended time period (see Schuman et al. 2002; Svejcar et al. 2008 for specific estimates). These values imply that gross income from sequestration activities will vary between \$1 · ha<sup>-1</sup> and \$10 · ha<sup>-1</sup> at currently projected C prices of ~\$10 · T<sup>-1</sup>. If overhead costs are to remain at less than 10% of the value of the commodity, the cost of verification and conveyance activities must be limited to between \$0.10 · ha<sup>-1</sup> and

\$1.00 · ha<sup>-1</sup>. To date, US prices for GHG mitigation activities have not approached this target level. Furthermore, these prices likely will not persist, because they reflect short-term commitments and do not account for issues related to the permanence of soil C pools or the fact that rates of soil C sequestration decline as C pools approach saturation (West and Six 2007; Kim et al. 2008).

Mitigation strategies have the potential to reduce the economic viability of rangeland production systems (Ritten et al. 2012) and increase commodity prices, including those for livestock (Baker et al. 2010). Specific issues contributing to increased production costs include limited management flexibility, taxes, or other assessments on C emissions associated with fuel and fertilizer production, and CH<sub>4</sub> emissions resulting from manure production and enteric fermentation (McCarl and Schneider 2000, 2001). Additionally, verification to account for the ecological and transactional uncertainties will reduce payments available to land owners for GHG offset projects (Kim and McCarl 2009; Ritten et al. 2012). However, mitigation need not adversely affect rangeland economies, especially in the longer term. For example, reducing fossil fuel-derived inputs should increase economic returns in livestock production systems (Zilverberg et al. 2011). Rangeland investments currently are hampered by low economic returns and the frequent absence of incentives to invest in improvements, particularly on rented/leased public lands (Torell et al. 2005; Havstad et al. 2007). Economic returns from a C market or public incentives could lead, in the long term, to management that both increases C sequestration and improves rangeland condition and productivity (Brown and Sampson 2009). For most US rangelands, grazing management to optimize net return per unit of land area is consistent with achieving C sequestration benefits (Dermer and Schuman 2007; deStieguer 2008). Likewise, proven technologies for cost-effective management of extensive rangeland-based livestock production systems are consistent with optimizing emissions of CH<sub>4</sub> and N<sub>2</sub>O (Liebig et al. 2010). Whether these emission reductions and sequestration increases can be sufficiently documented to meet market standards will determine the ability of rangeland managers to profit from markets.

A thorough assessment of the ecological and social considerations affecting C sequestration on US rangelands has produced the following recommendations (Booker et al. 2013). First, short-term accounting is ill-advised, given the high transactions costs associated with measurement of low and highly variable C fluxes. Second, policies should not assume that specific management practices will always promote C sequestration and therefore, credits should not be directly linked to these practices. Third, policies should seek to conserve existing C on rangelands and restore soil C by converting marginal croplands to perennial vegetation.

## ADAPTATION TO CLIMATE CHANGE

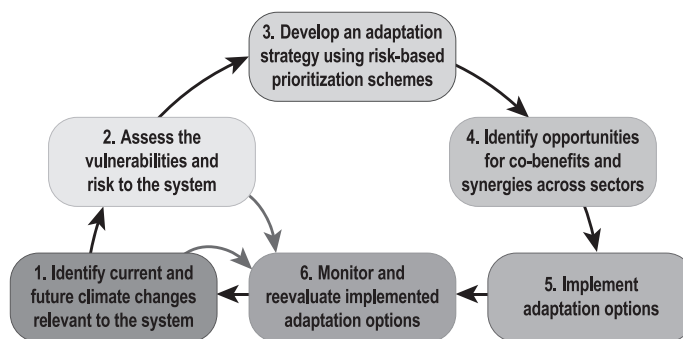
Adapting to climate change requires an understanding of the vulnerabilities of social-ecological systems and the development of policies and management alternatives to enhance the adaptive capacity of these systems to respond to known vulnerabilities and potential surprises. Adaptation planning

and action will be critical across all levels of government as well as within the private sector, nongovernmental organizations, and community organizations (NRC 2010). For example, US federal agencies are now developing sustainability plans to address emission reductions and climate change adaptation in response to Executive Order 13514 (US White House 2009; see also Bierbaum et al. 2013). In the private sector, the insurance industry is incorporating climate science into risk exposure and management, and is working with clients to facilitate adaptation to climate change and to reduce GHG emissions (Mills 2012). Yet, until recently, adaptation to climate change has been a low national priority, so relatively little information and few systematic approaches exist for its development (NRC 2010; Berrang-Ford et al. 2011). Information that does exist has seldom been interpreted in ways that are relevant to rangeland managers and it has not been effectively integrated into management planning (Hoffman 2010; Stafford Smith et al. 2011).

### Adaptation Planning

Adaptation can be envisioned as an iterative risk-management strategy that is based on the process of learning and adjusting, rather than on adherence to a prescribed set of technologies and policies (Nelson et al. 2007; NRC 2010). Adaptation first involves a careful assessment of the feasibility of maintaining current management goals based upon anticipated climate changes, as well as frequent evaluation of progress toward the attainment of established goals (Fig. 2). Climate change alters known risks and introduces new risks, essentially modifying the risk profile of the social-ecological system. Vulnerability assessments can be used to analyze the implications of these changes (step 2, see also Supplementary Materials). At the scale of the ranch enterprise, a vulnerability assessment can provide information to prioritize management strategies in light of potential changes in climate. At the regional or national scale, the assessment could be used to prioritize production enterprises and social-ecological systems relative to the magnitude of harm and the anticipated rate at which adverse consequences might occur in response to climate change. Such an assessment could identify opportunities or barriers to adaptation that could be facilitated by broader-scale developments, including modification of government policy, development of new scientific findings, and potentially increased public investment.

Adaptation options (step 3) should be designed to increase the resilience of social and ecological systems to change (Table 1). Resilience has become an accepted framework for management of social-ecological systems in the face of rapid and unprecedented change—conditions in which prescriptive management is of limited value (Walker and Salt 2012). An explicit goal of resilience management is to sustain opportunities for systems to supply ecosystem services to society (Chapin et al. 2009). However, an ecosystem-service-based approach will require development of new concepts and tools to quantify existing and newly recognized ecosystem services and their monetary values, assess tradeoffs, and develop markets (Brown and MacLeod 2011). Although some services have been traded as commodities for centuries (e.g., food, fiber, and fire wood), new services (e.g., C sequestration, water yield, viewsheds, and cultural values) will require new measurement



**Figure 2.** The adaptation planning process is envisioned to incorporate the following steps: 1) identify current and future climate changes relevant to the system, 2) assess the vulnerabilities and risk to the system, 3) develop an adaptation strategy using risk-based prioritization schemes, 4) identify opportunities for co-benefits and synergies across sectors, 5) implement adaptation options, and 6) monitor and reevaluate implemented adaptation options (Figure 4.1 in NRC 2010).

procedures and markets (steps 4 and 5). The development and application of new procedures and markets to enhance resilience will require the capacity to create and organize knowledge of system components and their interactions and the reorganization or development of organizations to extend and apply this knowledge (Nelson et al. 2007; Pelling 2011).

Given the potential for continuous change in climate, adaptation planning will require continued development of adaptive capacity so that newly emerging conditions and opportunities can be addressed within these systems (Nelson et al. 2007; Pelling 2011). The potential exists to reduce adaptive capacity (maladaptation) by minimizing flexibility and deferring risk to a later time or to other sectors of social-ecological systems (Pelling 2011). Therefore, specific adaptation actions should be thoroughly analyzed for their short- and long-term effects (life cycle analysis; Finnveden et al. 2009; de Vries and de Boer 2010) to minimize the possibility of increasing exposure and vulnerability in the future (NRC 2010). Toward this end, monitoring is critical to effective evaluation of adaptation strategies in social and ecological systems (step 6) by providing information to evaluate progress toward adaptation goals and to identify desirable modification to adaptation strategies (Millar et al. 2007; Joyce et al. 2008; Morgan et al. 2008).

The overall effectiveness of adaptation to climate change rests on four major considerations (Adger and Barnett 2009; Stafford Smith et al. 2011). First is the window of opportunity available for development and implementation of adaptation strategies. In some cases, this window might be smaller than previously assumed, based on the rate of climate change and the potential occurrence of thresholds in the climate system (Lenton et al. 2008). Second, the development of adaptation strategies, regardless of their potential effectiveness, is dependent upon sufficient financial and political capital to implement them in a timely and meaningful manner. Third, many current adaptations are unsustainable or maladaptive, and their limited effectiveness can slow the development and implementation of subsequent adaptations. Fourth, metrics of adaptation success are inherently more ambiguous than those for mitigation because they do not have a specific, measurable benchmark



such as GHG emissions, and will vary with values and interests of various stakeholder groups (Berrang-Ford et al. 2011).

There is also a legitimate concern that an overly simplified approach to adaptation could invoke a false sense of security regarding the consequences of climate change by suggesting that all climate-related challenges are manageable. This concern is especially the case for adaptation to known risks, such as drought or increased fire frequency, because these events can be viewed historically, their impacts on humans are relatively well understood, and the expectation of optimal economic solutions seems plausible (Eakin et al. 2009). However, these retrospective reconstructions mask uncertainty about the drivers of change and critical interactions, and stifle awareness of associated climate surprises that can potentially exacerbate system vulnerability. Similarly, the call for more precise regional climate projections can overemphasize optimal decision-making based on an unwarranted assumption of accuracy of climate change projections when a more robust approach to adaptation and decision-making might prove more successful, i.e., resilience thinking (Dessai et al. 2009).

### Adaptation Strategies

Rangeland social-ecological systems, production enterprises, and management actions and goals differ widely; no single adaptation strategy is applicable to all rangeland systems, all situations, and over both short and longer time frames. In addition, the human capacity for learning and implementing responses to lessons learned offers a myriad of opportunities for reducing exposure, predicting and detecting sensitivity, and expanding adaptive capacity (Marx et al. 2007; Marshall 2010). Adaptation is a dynamic, iterative process in that social-ecological systems will continue to respond to continual climate change, and the adjustments implemented through adaptive management will further modify the conditions that dictate the most appropriate adaptation strategies (Fazey et al. 2010). This underscores the importance of nurturing and building human capacity to continuously evaluate values, structures, and outcomes in the social-ecological system (Pelling 2011).

Adaptation strategies must be developed for both the short-(near-) and long-term in order to identify and maintain the maximum number of adaptation options for future consideration (Fazey et al. 2010). Short-term adaptation strategies could involve easily implemented practices, or “low hanging fruit,” that increase the capacity of ecosystems to retain their structure and function in the face of climate change by reducing the detrimental impacts of these changes or other related stressors (Millar et al. 2007). Many forms of adaptation relevant to rangelands can be considered “no-regrets” strategies because they can be justified *without* emphasis on pending climate change. For example, climate change is likely to exacerbate the effects of drought, invasive species, and wildfires (NRC 2010; Polley et al. 2013 [this issue]). Intensified management for these stresses thus will contribute to climate change adaptation (Millar et al. 2007; Joyce et al. 2008). The development of adaptation strategies for the longer-term usually requires greater information and investment and, in some cases, societal support or policy development (NRC 2010). Those who initiate these developments must be

cognizant of the likelihood of gradual transitions to unique plant communities and enterprise structures, and modifications in labor demands, market availability, as well as other socio-economic variables. The success of these strategies must be assessed relative to environmental, social, and economic benefits within the context of the new climatic conditions (Joyce et al. 2009).

### Adaptation Strategies for Livestock Production Enterprises

Few of the specific adaptation strategies that have been proposed (CCSP 2008; Heller and Zavaleta 2008; Bierbaum et al. 2013) have focused on rangelands and livestock production (e.g., Polley et al. 2000; Morgan et al. 2008; Izauralde et al. 2011). Strategies for livestock production involve changes in grazing management, livestock breeds or species, pest management, enterprise structure, and even the geographic relocation of livestock production systems to contend with likely impacts of climate change (Table 3). This section primarily emphasizes “within ranch gate” strategies and does not address broader concerns of transportation, meat processing, and the cost and availability of water and energy.

**Grazing Management.** Conservative stocking rates, varied season of grazing, flexible stocking strategies, and the development of income diversification strategies can minimize climatic impacts and promote ecological and economic viability (Morgan et al. 2008; Torell et al. 2010; Coppock 2011). Herd size and composition, identification of reserve forage, water availability and distribution, and forage-dependent stocking strategies can be examined in the short term (see “no-regrets” strategies; Table 3) as strategies to respond to drought (Thurow and Taylor 1999; Torell et al. 2010; Coppock 2011). For example, in a northern Australian rangeland, financial returns after 12 yr of variable precipitation were maximized by adjusting stocking rates based on available forage, followed closely by set-stocking at a moderate rate (O’Reagain et al. 2011).

Adaptation strategies developed by broader institutions or governments can also be opportunities for engagement by the ranch enterprise. Increased coordination between the private sector and local to federal governmental agencies on drought planning and drought-related policies (e.g., fire closures of public lands, grazing management) could further reduce the ecological and social effects of drought and increase system resilience. At the federal level, the USDA Risk Management Agency has developed Pasture Rangeland and Forage Insurance to help livestock producers deal with the risk associated with drought.<sup>1</sup> This program allows producers to purchase insurance to help reduce financial impacts of drought and is subsidized 51% by the US government (Berger 2013).

**Livestock Breeds, Classes, and Species.** A shift in the breed, class, or species of livestock is one of the more readily-implemented adaptation strategies available to rangeland managers (Table 3). Most cattle raised in the western United States were developed from European breeds that possess a relatively low tolerance to high temperatures (Kay 1997; Hoffman 2010; O’Neill et al. 2010; Polley et al. 2013 [this

<sup>1</sup>Available at: <http://www.rma.usda.gov/policies/pasturerangeforage/>. Accessed 27 February 2013.

**Table 3.** Specific adaptation options organized into the three broad strategies of “no regrets,” anticipatory and planned across enterprise, human, and social categories. “No regrets” strategies can be justified without emphasis on pending climate change. Anticipatory strategies occur when climate change impacts are acknowledged as likely and adaptive responses are planned but not implemented until climate change occurs. Planned strategies result when adaptation responses are developed and implemented before climate-induced changes are observed.

Adaptation category	Degree of adaptation	
	“No regrets”	Anticipatory
Enterprise	<ul style="list-style-type: none"> <li>• Enhance invasive species monitoring and control</li> <li>• Enhance drought management</li> <li>• Evaluate short-term weather forecasting to support forage inventory and stocking decisions</li> <li>• Evaluate alternate income sources, such as ecotourism, carbon management, alternative energy sources</li> <li>• Conservation stocking: extend forage supply, reduce feed costs, ecological restoration</li> <li>• Grazing season: match forage quality and supply with animal requirements</li> <li>• Evaluate cow size: smaller animals require less intake and have higher feed efficiency</li> <li>• Evaluate fire management: fuel management, prescribed burning, zoning in rural–urban interface</li> </ul>	<ul style="list-style-type: none"> <li>• Evaluate environmental and economic risk in grazing resources associated with current management plan</li> <li>• Evaluate the use of drought-resistant species in forage planting</li> <li>• Enhance drought planning to include: herd size, composition, reserve forage, destocking strategies</li> <li>• Plan for revenue diversification: diversify services supplied, value added, other income sources</li> <li>• Address forage quality shifts by evaluating supplemental feeding options</li> </ul>
Human	<ul style="list-style-type: none"> <li>• Identify risk perception and willingness to adopt change</li> <li>• Minimize perception of climatic consistency and anticipate change</li> <li>• Evaluate long-term family values and goals: conservation, production, life style</li> <li>• Seek out information on climate changes in your geographic area</li> <li>• Participate in social learning and other information networks</li> <li>• Implement adaptive management to the extent possible</li> <li>• Cultivate social networks to enhance adaptive capacity to current extreme events (drought, extreme storms, heat events)</li> <li>• Identify perverse incentives that encourage less-resilient management and high risks</li> <li>• Develop policies and incentives to support effective resource and risk management</li> </ul>	<ul style="list-style-type: none"> <li>• Change cattle breed such as from <i>Bos taurus</i> to <i>Bos indicus</i></li> <li>• Change class of animal: stocker vs. cow–calf for greater flexibility</li> <li>• Change species from cattle to sheep or goats</li> <li>• Shift livestock breed to address increased pests (e.g., breeds resistant to horn fly)</li> <li>• Nitrogen supplementation: targeted to offset declines in forage quantity/quality</li> <li>• Initiate use of novel ecosystems: forage supply, carbon sequestration, biofuels</li> <li>• Implement revenue diversification: diversify services supplied, value added, other income sources</li> <li>• Relocate production enterprises: cow-calf systems move north to support consistent production</li> <li>• Evaluate economic risk of current enterprise structure and implement structural changes; from livestock to include wildlife and/or energy development</li> <li>• Evaluate markets for new products and services</li> </ul>
Social organizations	<ul style="list-style-type: none"> <li>• Work with professional networks to conduct a vulnerability assessment of the landscape or region</li> <li>• Work with extension or other professionals to evaluate economic feasibility of new products from the enterprise</li> <li>• Explore the valuation of ecosystem services</li> <li>• Evaluate regional labor availability for changes in enterprise structure</li> </ul>	<ul style="list-style-type: none"> <li>• Facilitate engagement among scientists and managers to enhance the usability of climate change scientific information for rangeland management</li> <li>• Seek private or governmental support to establish the infrastructure to develop markets for alternative products from the ranch enterprise</li> <li>• Evaluate the adaptive capacity of rural communities to climate change</li> </ul>

issue]). *Bos indicus* cattle (e.g., Brahmans) are generally more tolerant to heat stress than *Bos taurus* (English and Continental) breeds; higher temperatures, potentially lower quality feed, and higher disease levels under climate change could be additional factors to consider in cattle breeding programs (Hoffmann 2010; O'Neill et al. 2010). Zhang et al. (2013) found a greater incidence of Brahman and Brangus than Angus breeds of cattle in hotter regions of Texas, evidence that many managers have already shifted breeds as a means of adaptation to higher temperatures. Although this shift facilitates cattle production in warm climates, O'Reagain et al. (2009) noted that the expansion of *Bos indicus* cattle in northern Australia also allowed grazing pressure to be maintained in the most severe droughts.

Livestock species can be replaced to better match climate and forage class and availability (Kay 1997; Seo and Mendelson 2008; Seo et al. 2010). Sheep and goats are more heat tolerant, require less water, and can consume a wider array of forage types than cattle and might be better suited to exploit anticipated changes in the forage base (see Izaurralde et al. 2011), including reduced forage quality (Hofmann and Stewart 1972). Smaller ruminants require less forage, and have slightly higher production efficiency per unit of protein than larger ruminants such as cattle (Dickerson 1978). Goat production could shift westward into some rangelands if climate change shifts the forage base toward increased shrubby and woody species, or invasive species as anticipated (Glimp 1995). Increased access to technical information and sponsored demonstrations could facilitate these large-scale shifts to alternative livestock species.

The availability of markets for these alternative livestock products influence when and where the livestock shifts could occur. Production of meat and milk goats, in particular, has increased rapidly from 1997 to 2006 in the southeastern United States in response to changes in demand associated with ethnic diets (Solaiman 2007) and an increased availability of small, relatively productive land units following changes in land use (e.g., tobacco buyout). Alternatively, even though the use of Brahman animals has expanded, the meat of Brahman animals has lower consumer acceptability because it is less tender and contains less marbling than that of European cattle breeds (Koch et al. 1982), thus generating lower market returns (Zhang et al. 2013).

**Pest Management.** Climate change can lead to more frequent and severe impacts of both native and invasive insect species, diseases and invasive plants that can reduce forage production and quality and affect livestock health (Ryan et al. 2008; Ziska et al. 2011; Walthall et al. 2012; Polley et al. 2013 [this issue]). Currently available management strategies such as detection/prediction, biological control, physical control, and chemical control, could be intensified to address these biotic agents in response to climate change. Monitoring points of entry and rapid eradication, as exemplified by the USDA early detection and rapid response program, will continue to be important with respect to invasive species (Ziska et al. 2011). Monitoring at the scale of the enterprise will also be important to identify changing pest concerns.

Innovative pest management solutions will be required to address the challenge of insect pests of livestock because it

might not be economically or environmentally sustainable to continue to rely on chemical control of livestock ectoparasites (Pruett 2002). Alternatives to chemical controls include the use of resistant livestock breeds, selection of resistant animals within a breed, immunization, and use of alternatives to chemical pesticides. For example, horn fly resistance appears to be highly heritable (Brown et al. 1992; Pruett 2002). Concerns about chemical management suggest that novel approaches, such as habitat manipulation for insect herbivores (Branson et al. 2006) or prescribed fire to alter parasite communities, be considered (Scasta et al. 2012).

Early studies on chemical control of invasive plant species indicate a potential decline in chemical efficacy under climate change and elevated CO<sub>2</sub>, with little understanding of the mechanisms (Ziska et al. 2011). Climate change could also alter the efficacy of biological control, given that climate change is likely to affect predator and prey species differently, and this too remains an important research area. Ziska et al. (2011) indicate that rising CO<sub>2</sub> levels could increase the root-to-shoot ratio of some invasive plant species and thereby both enhance the capacity of these plant species to reproduce asexually and reduce the current efficacy of mowing and grazing as a control practice.

**Enterprise Structure.** Past production efficiencies and market pressures have led to changes in enterprise structure, and shifts in geographic distribution of beef production and industry structure. In the mid-20th century, many livestock managers moved from integrated cow-calf, stocker-feeder operations to more specialized operations to take advantage of forage conditions and to reduce risk (MacDonald and McBride 2009). Cow-calf operations shifted to the southeast where milder winters and higher rainfall provided a consistent forage supply to support animal reproductive efficiency. Stocker operations replaced traditional cow-calf enterprises in the tallgrass prairie of the eastern Great Plains because stockers could effectively utilize the large amount of high-quality forage produced during the first half of the growing season (Owensby et al. 1973). Feedlot finishing operations shifted from the upper Midwest to the High Plains to take advantage of the readily available source of grain produced on irrigated croplands. Similarly, diversification of rangeland enterprises has been implemented through management practices, land tenure arrangements, products, marketing, and services, including ecosystem services that are not yet marketable (Sayre et al. 2012). These changes occurred in response to: 1) economic concerns emphasizing efficiencies of scale, 2) human demographics as reflected in aging and absentee landowners who desired to reduce risk, and 3) climatic considerations focused on matching animal physiological needs with forage production cycles.

Future changes in ecological, economic, and social variables, including land use change, likely will drive additional changes in livestock production systems (Reilly et al. 2002; McBride and Mathews 2011), including the geographic location of production systems. For example, urbanization will continue to pressure rangeland area surrounding cities (USDA Forest Service 2012) and the arid West is likely to be affected by energy development on rangeland—oil and gas development as well as solar (Kreuter et al. 2012; Reeves and Mitchell 2012).

In addition, the demand for energy crops could shift cropland and pasture to perennial bioenergy crops, resulting in a loss of land area directly supporting livestock production. This change in forage availability could accelerate the shift of cropland pasture to hay production or private rangeland pasture to cropland pasture (Dale et al. 2011).

Climate change, in combination with ecological and social variables, will likely force further shifts in the geographic location of major rangeland production enterprises. Reduced stocking rates, conversion of cropland to rangeland, and shifting the loci of cattle production and processing operations into more suitable areas could be viable adaptation strategies for responding to warmer and drier climatic conditions (McCarl 2007, 2011; Mu et al. 2013). For example, warming and drying will likely reduce livestock production in the southern plains and southwestern United States, but it might increase production in the northern states and southern Canada by increasing plant production and minimizing low-temperature stress on livestock (Thorpe et al. 2008; Kulshreshtha 2011; Polley et al. 2013 [this issue]). Alternatively, an enterprise might shift from livestock production to ecotourism, hunting, wind energy, or C sequestration (i.e., mitigation strategy) if climate change reduces the economic viability of traditional production systems (Morgan et al. 2008, 2010; deSteiguer 2008). In addition to product diversification, adaptation at the level of the enterprise might require a change in the perception of acceptable levels of ecological and social risk, and change in the social capital or infrastructure devoted to land management in order to remain economically viable (Adger et al. 2007; Walthall et al. 2012).

### **Building the Capacity to Implement Adaptation Strategies**

The availability of appropriate adaptation strategies is critical in responding to climate change, but equally important are availability of information, experience and training, social and economic incentives, and the organizational and institutional resources to facilitate their implementation (Popp et al. 2009; Fazey et al. 2010; Moser and Ekstrom 2010; Marshall et al. 2011). Local opportunities are needed to expand technical skills for climate-smart management, strengthen professional networks, support organizations to increase opportunities for climate change education, enhance adaptive capacity in the form of skills and staff, and create social networks or communities of practice within and among private, local, state, and federal agencies (Peterson et al. 2011; Bierbaum et al. 2013). The successful use of advances in rangeland science in management and decision-making will be dependent upon the emergence of social organizations that can facilitate the integration of this information across the social-ecological system (Sayre et al. 2012; Bestelmeyer and Briske 2012). The Climate Adaptation Knowledge Exchange (CAKE) is an example of an organization focused on integrating and sharing information, data tools, and on-the-ground adaptation practices, as well as connecting a community of practitioners to enhance ecosystem management with climate change.<sup>2</sup> Professional societies, such as the Society for Range Management, can play a lead role in the development of communications strategies to raise awareness of climate change, its potential

<sup>2</sup>Available at: <http://www.cakex.org/about>.

impacts, and the advantages of early attention to adaptation. Partnerships with other professional organizations and agencies could facilitate integration of diverse climate change knowledge into education and training materials, development of best practices networks, and the establishment of standards for viable adaptation practices.

The variable nature of ecological and social systems, as well as potential mismatches in the timing or scale of events, such as drought or market failures, constrains learning and the development of adaptive capacity (Stafford Smith et al. 2007). Currently, many rangeland enterprises perpetually remain in a “drought trap” with limited capacity to cope with more frequent and severe drought events (Coppock 2011). For example, a very small percentage (14%) of rangeland enterprises were prepared for the 1999–2004 drought in Utah, as evidenced by data on livestock sales, hay purchases, and the large number of requests for federal drought relief and “crisis” water development (Coppock 2011). The percentage of enterprises that were prepared for the subsequent drought in 2009 only increased to 29%. Drought preparedness was strongly influenced by a manager’s experience in the previous drought and the perception that another drought was imminent. This lack of response, also termed an “adaptation deficit,” has been partly ascribed to drought relief programs, interpreted as perverse incentives that encourage a lack of preparedness for what is an inevitable occurrence on most rangelands (Thurow and Taylor 1999). In other examples, social considerations, rather than physical vulnerability to climate change (e.g., availability of water), are known to determine managers’ perception of the risk of climate change (Marx et al. 2007; Moser and Ekstrom 2010; Safi et al. 2012). Similarly, strategic skills, environmental awareness, and social capital exceeded technical considerations as determinants of adaptation planning for grazers in Australia (Marshall et al. 2011).

Integrating information on climate change, impacts, and adaptation options into the decision-making process has been seen as a critical role for vulnerability assessments, yet implementation of adaptation management has not followed necessarily from these assessments (Preston et al. 2011; Yuen et al. 2013). More broadly, it has been well documented that the use of climate change science information is under-utilized in decision making (Marshall 2010; Dilling and Lemos 2011). For example, ranch managers in Australia perceive themselves to be resilient to climatic variability, yet only about 40% utilize scientific information such as seasonal climate forecasts (Marshall 2010). Dilling and Lemos (2011) stress that successful use of science in decision making requires the purposeful and strategic interaction between the producers and users of knowledge. Professional organizations, particularly those focused on the intersection of resource management and science, can have an integrative role engaging their membership in strategic thinking about information needs to mitigate and adapt to climate change within various enterprises as well as in regulation and policy.

Adaptive capacity varies greatly among land owners and managers, even within specific regions, creating a “social heterogeneity” in human emotional and financial flexibility, interest in adapting to climate change, and capacity to manage risk, and to plan, learn and reorganize (Marshall and Smaigl

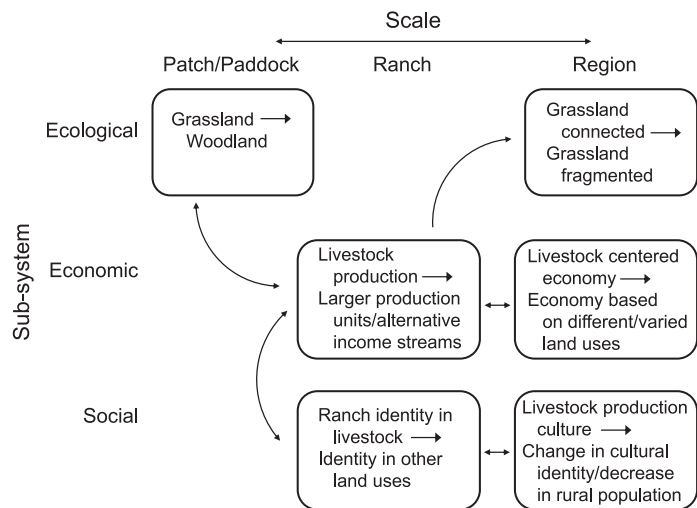


2013). This heterogeneity results in the daunting task of identifying what different land owners and manager are willing to learn and implement as adaptation. It has been suggested that social learning should play a greater role in adaptation planning, and vulnerability assessments in particular (Yuen et al. 2013). Social learning, or collective learning, is a process where human values, goals, and knowledge can be shared so that collective actions can be taken (Yuen et al. 2013). The Malpai Borderlands Group (MBG) is an example of self-organization and active or collaborative learning (Gunderson et al. 2006) where private landowners, environmental organizations, and state and federal agencies responded to the threat of landscape subdivision and development and the risk of declining productivity and loss of biological diversity that accompanies woody species encroachment. In the MBG, scientists and technical advisors worked directly and continuously with landowners and managers to use the best available science and technology to achieve objectives. This collaboration has resulted in more relevant science and more effective adaptive management, including grass banking.<sup>3</sup>

Most adaptation strategies incorporate management practices to reduce the physical or biological impacts of climate change; however, few adaptation strategies incorporate socio-economic incentives to encourage human behavior toward management to sustain resilient ecosystems (for example, sustained drought management, Marshall 2010; Marshall and Smaigl 2013). For example, flexible grazing management strategies, including a combined cow-calf and yearling operation, produce greater economic return than a set conservative strategy (Torell et al. 2010), yet these strategies are infrequently adopted because decision makers perceive that these strategies increase financial risk. Increased climatic variability will require greater flexibility in forage sources (i.e., grass banks, hay supplies), increased contingency planning, and the ability to alter herd sizes and production systems, all of which require a financial buffer and could be advanced using financial incentives (Adger et al. 2007; Morgan et al. 2008). Local knowledge might be insufficient on its own for sustainable management (Stafford Smith et al. 2007); hence, it will be important for emerging social organizations to integrate local knowledge and emerging scientific information so that learning systems across the local to regional scale can identify and facilitate financial incentives and institutional support for adaptation.

### WHEN ADAPTATION FAILS: TRANSFORMATIONAL CHANGE

It is generally assumed that incremental adaptation will be sufficient to a warming threshold of 2°C (i.e., dangerous climate warming), but limited actions to reduce global GHG emissions indicate that this threshold will be attained and surpassed (Adger and Barnett 2009; Stafford Smith et al. 2011). In these cases, climate change is likely to create situations where it is not economically or ecologically feasible to alter management and organizational resources sufficiently to preserve the functions supporting desired ecosystem services (Joyce et al. 2008; Kates et



**Figure 3.** Transformational change often involves simultaneous or reinforcing changes in different domains (ecological, economic, and social/cultural) and at multiple spatial scales. The figure is adapted from Kinzig et al. (2006).

al. 2012). For example, managers might find that it is not economically sustainable to compensate for the expected decline in forage quality associated with increasing CO<sub>2</sub> concentration, temperature, and drought (Morgan et al. 2008) or the anticipated change in plant species composition (Polley et al. 2000). In these instances, economic and ecological constraints might compel a change in enterprise structure to emphasize production of alternative ecosystem services. These conditions could arise from a rapid acceleration of climate change in specific regions (i.e., climate hotspots), and maladaptive practices that predispose systems to threshold type collapse (Adger and Barnett 2009; Kates et al. 2012). Transformation, by definition, transcends incremental adaptation and requires new and novel interactions between the social and ecological subsystems. The emphasis in transformation is on provisioning “new” ecosystem services—ecotourism, hunting leases, C sequestration—that emerge as social-ecological systems shift to accommodate ecological change or modification in the availability of land, labor, and capital (Walker and Salt 2012).

Woody plant encroachment has contributed to, and likely will continue to contribute to, the transformation of rangeland systems (Fig. 3). Adaptive management might be able to respond successfully to increases in the shrub:grass ratios on grazed rangelands by changing grazing season, altering livestock genetics or even livestock species, or providing supplemental feed (see previous section on Adaptation). However, in some social-ecological systems, the balance might shift so strongly toward shrub dominance that the continued production of grazing livestock is impossible to maintain. In other cases, ecological systems might remain relatively stable as expressed in the shrub:grass ratio, but the social subsystem will no longer support livestock production. A social subsystem can collapse from a lack of capital or a labor shortage in depopulating rural areas and declining consumer demand or increasing international competition for specific products. Transformational change of one subsystem can destabilize another subsystem to eventually transform the entire social-

<sup>3</sup>Available at: <http://www.malpaiborderlandsgroup.org>.

ecological system via a process of linked, cascading effects (Park et al. 2012; Walker and Salt 2012; Fig. 3). It is also possible that both the ecological and economic subsystems will simultaneously collapse as occurred during the Dust Bowl of the 1930s in the United States.

Although much less socially disruptive, such an event might currently be underway in the southern Plains region in response to the droughts of 2011–2012 (Peel 2013). The majority of livestock are held primarily in small (< 250) herds, dependent on a wide variety of forages. The severe drought and high hay prices forced producers to sell animals. A decline in the national beef cow herd has kept prices for replacement stock high, and difficulty in accessing credit has greatly limited the ability of producers to reestablish their cow herds. Simultaneously, demand for land for low density development in the region is driving land prices higher. These social and economic forces are compelling many livestock producers to sell out. This changing matrix of landowners with widely disparate objectives for land use and management can greatly complicate the interpretation, packaging, and delivery of research into extension and assistance programs. This type of multiscale transformation could ultimately restructure the social, economic and ecological nature of landscapes, making them more vulnerable to a host of potential threats, including wildfire, invasive species, and fragmentation.

The capacity of social-ecological systems to successfully manage transformation depends on five key considerations: *awareness*, *incentives*, *networks*, *experimentation*, and *assets*. *Awareness* of the need to implement transformative strategies depends on human ability to recognize and broadly communicate impending changes in the ecosystem services derived from a social-ecological system (Carpenter and Folke 2006; Marshall et al. 2011). Transformative change is difficult; hence, people and organizations do not want to embark on difficult journeys unless there is a compelling reason (Kates et al. 2012). Denial is often an immediate response that can be difficult to overcome (Walker and Salt 2012). Consequently, *incentives* might be required to encourage voluntary change (Osterblom et al. 2011). Deciding what to do and implementing those decisions are largely dependent upon the strength of *networks* and the ability of the participants to *experiment*, preferably at local to regional scales until cost-effective strategies have been established (Nelson et al. 2007; Folke et al. 2010). The Malpai Borderland Group illustrates how social and scientific organizations can successfully *network* to identify the changes in land management policies, programs, and actions required to respond to climate change. Finally, transformability requires flexibility in the *assets* or resources necessary to implement change. The ability to mobilize and direct critical financial, labor, and technical resources is considerably constrained when operating margins are narrow (Marshall et al. 2011). Recognizing and communicating the need for transformation and developing policies, programs, and actions to support determination of when and how to initiate transformational changes are important challenges for the rangeland profession.

## SYNOPSIS OF MITIGATION AND ADAPTATION STRATEGIES

- Climate change is a unique global event in that humans can implement actions to both affect the severity of climate change

through the rate of GHG emissions (mitigation) and mediate the ecological and social consequences of climate change (adaptation). Consequently, human goals and values, socio-economic responses, and political imperatives will exert a large and often decisive influence on the development and implementation of mitigation and adaptation strategies. It is important that both ecological and socio-economic components and their interactions be considered when devising such strategies.

- At the scale of the ranch enterprise, mitigation actions for C sequestration do not appear economically viable, given the small and highly variable CO<sub>2</sub> fluxes and proportionately high transaction costs. Current knowledge of C fluxes in rangeland systems indicates that policies and programs should focus on long-term strategies to protect existing C pools, rather than promote additional sequestration, with the clear exception of converting marginal cropland to perennial vegetation.
- Vulnerability of rangeland production enterprises to climate change is determined by a combination of social and ecological variables, including sensitivity to climatic variability, the extent to which climate change occurs, and the amount of adaptive capacity that can be developed within the local social-ecological system. Vulnerability of an enterprise is also affected by the response of regional, national, and international markets, governmental policies, and social dynamics to climate change.
- Effective adaptation strategies involve modifications within a linked framework of social and ecological systems to minimize detrimental consequences and capture opportunities arising from climate change. Climate change will alter the environmental and economic risk profile of the ranch enterprise; adaptation will be required to minimize the new and novel risks to ecosystem function, enterprise viability, and human livelihoods. Adaptation is an iterative process involving continuous adjustments and social learning to guide change in social-ecological systems.
- Adaptation strategies for livestock enterprises are numerous and varied, and will be unique to each situation. These strategies might include well-designed drought contingency plans, options for greater herd flexibility, heat- or drought-tolerant livestock breeds or species, adoption of innovative pest control methods, diversification of the enterprise, and in extreme cases, a shift in structure or location of production systems.
- Climate change is likely to create conditions in which the investment required to “adapt” might exceed the economic return or desired social benefits or is ecologically improbable. In these cases, it will be necessary for social-ecological systems to transform to a new configuration and to develop new ways of operating that include the production of alternative ecosystem services with novel management approaches and production systems.

## MANAGEMENT IMPLICATIONS

A conservative interpretation of contemporary climate change science and GHG emission trends indicates that there is a high probability of future deviation from long-term climatic trends,

as well as increasing variability around these trends. The direct and indirect effects of these changes are likely to substantially modify ecosystem function and the services and livelihoods provisioned. This establishes a clear need to develop adaptation strategies to contend with these changes, even though precise forecasts of climate change are not available. The challenges posed by increasing climatic variability on rangelands are illustrated by the “adaptation deficit” that exists to current climatic conditions, especially regarding limited adoption of flexible grazing management strategies and implementation of effective drought management planning. Development and implementation of effective adaptation strategies will require that the pervasive perception of climatic consistency as exemplified by the development of “crisis” management policies be replaced by greater awareness and preparedness for climatic variability and uncertainty.

Adaptation is a well-established concept in rangeland systems, but the anticipated rate of climate change, in conjunction with major changes in land use patterns, globalized agricultural markets, and increasing competition and costs for resources that traditionally were dedicated to livestock production (e.g., land, water, and feedstocks), might render previous management and policy recommendations inappropriate. New approaches are required to anticipate, plan for, and minimize the detrimental consequences of climate change, and to recognize and capture opportunities that arise from these altered conditions. These approaches will involve a diverse scope of options, including altered risk perception and aversion by individuals, greater flexibility of production enterprises, and modifications to social organizations that will collectively emphasize the variability, rather than the consistency of climatic conditions. Central to this approach for developing a framework of adaptation strategies is a system capable of monitoring and recording relevant information, defining risk assessment and management, assessing the effectiveness of various adaptation strategies and actions, and organizing multistakeholder partnerships that emphasize mutual support and information sharing (Meinke et al. 2009; NRC 2010; Stafford Smith et al. 2011). Adaptation over long planning horizons represents a dynamic, iterative process, rather than a static set of technologies or policies, and is founded upon adaptive capacity and social learning to continuously respond to rapidly changing social and ecological conditions.

The rangeland profession is uniquely positioned to address climate change adaptation and mitigation because it represents the intersection of management and scientific knowledge, includes stakeholders who derive their livelihoods either directly or indirectly from rangelands, and interacts with social organizations responsible for rangeland stewardship. The Society could support development of a database and decision-support framework capable of organizing the most relevant sources of information regarding adaptation and mitigation alternatives, address cost:benefit ratios, and provide a means to transfer the lessons learned. This synthesis supports the conclusion that the rangeland profession should draw upon its legacy and professional network to develop, extend, and promote implementation of multiple strategies to confront current and pending climatic variability and promote rangeland stewardship and human well-being.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the thoughtful reviews of William Fox, Dwayne Elmore, and two anonymous reviewers.

## LITERATURE CITED

- ADGER, W. N., S. AGRAWALA, M. M. Q. MIRZA, C. CONDE, K. O'BRIEN, J. PULHIN, R. PULWARTY, B. SMIT, AND K. TAKAHASHI. 2007. Assessment of adaptation practices, options, constraints and capacity. *In*: M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson [EDS.]. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. p. 717–743.
- ADGER, W. N., AND J. BARNETT. 2009. Four reasons for concern about adaptation to climate change. *Environment and Planning A* 41:2800–2805.
- ARCHER, S., T. W. BOUTTON, AND K. A. HIBBARD. 2001. Trees in grasslands: biogeochemical consequences of woody plant expansion. *In*: E.-D. Schulze, S. P. Harrison, M. Heimann, E. A. Holland, J. Lloyd, I. D. Prentice, and D. Schimel [EDS.]. *Global biogeochemical cycles in the climate system*. San Diego, CA, USA: Academic Press. p. 115–137.
- ASNER, G. P., A. J. ELMORE, L. P. OLANDER, R. E. MARTIN, AND A. T. HARRIS. 2004. Grazing systems, ecosystem responses and global change. *Annual Review of Environment and Resources* 29:261–299.
- AUSTRALIAN GOVERNMENT DEPARTMENT OF CLIMATE CHANGE AND ENERGY EFFICIENCY. 2013. Carbon Farming Initiative. Available at: <http://www.climatechange.gov.au/cfi>. Accessed 31 March, 2013.
- BAKER, J. S., B. A. MCCARL, B. C. MURRAY, S. K. ROSE, R. J. ALIG, D. M. ADAMS, G. LATTA, R. H. BEACH, AND A. DAIGNEAULT. 2010. Net farm income and land use under a U.S. greenhouse gas cap-and-trade. *AAEA Policy Issues* 7. Available at: <http://www.choicesmagazine.org/magazine/pdf/PI7.pdf>. Accessed 31 March 2013.
- BERGER, A. 2013. Pasture rangeland forage insurance is a risk management tool for 2013. UNL Beef. Lincoln, NE, USA: University of Nebraska–Lincoln. 2 p.
- BERRANG-FORD, L., J. D. FORD, AND J. PATERSON. 2011. Are we adapting to climate change? *Global Environmental Change* 21:25–33.
- BESTELMEYER, B. T., AND D. D. BRISKE. 2012. Grand challenges for resilience-based management of rangelands. *Rangeland Ecology & Management* 65:654–663.
- BIERBAUM, R., J. B. SMITH, A. LEE, M. BLAIR, L. CARTER, F. S. CHAPIN III, P. FLEMING, S. RUFFO, M. STULTS, S. MCNEELEY, E. WASLEY, AND L. VERDUZCO. 2013. A comprehensive review of climate adaptation in the United States: more than before, but less than needed. *Mitigation and Adaptation Strategies for Global Change* 18:361–406.
- BOOKER, K., L. HUNTSINGER, J. W. BARTOLOME, N. F. SAYRE, AND W. STEWART. 2013. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? *Global Environmental Change* 23:240–251.
- BRANSON, D. H., A. JOERN, AND G. A. SWORD. 2006. Sustainable management of insect herbivores in grassland ecosystems: new perspectives in grasshopper control. *BioScience* 56:743–755.
- BREMER, D. J., AND J. M. HAM. 2010. Net carbon fluxes over burned and unburned native tallgrass prairie. *Rangeland Ecology & Management* 63:72–81.
- BRIGGS, J. M., A. K. KNAPP, J. M. BLAIR, J. L. HEISLER, G. A. HOCH, M. S. LETT, AND J. K. MCCARRON. 2005. An ecosystem in transition: causes and consequences of the conversion of mesic grassland to shrubland. *BioScience* 55:243–254.
- BRISKE, D. D., N. F. SAYRE, L. HUNTSINGER, M. FERNANDEZ-GIMENEZ, B. BUDD, AND J. D. DERNER. 2011. Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. *Rangeland Ecology & Management* 64:325–334.
- BROWN, A. H., JR., C. D. STEELMAN, Z. B. JOHNSON, C. F. ROSENKRANS, JR., AND T. M. BRASUJELL. 1992. Estimates of repeatability and heritability of horn fly resistance in beef cattle. *Journal of Animal Science* 70:1375–1381.
- BROWN, J. R., J. ANGERER, S. W. SALLEY, R. BLAISDELL, AND J. W. STUTH. 2010. Improving estimates of rangeland carbon sequestration potential in the US Southwest. *Rangeland Ecology & Management* 63:147–154.
- BROWN, J. R., AND N. MACLEOD. 2011. A site-based approach to delivering rangeland ecosystem services. *The Rangeland Journal* 33:99–108.



- BROWN, J. R., AND N. SAMPSON. 2009. Integrating terrestrial sequestration into a greenhouse gas management plan. *In*: B. McPherson and E. T. Sundquist [EDS.]. Carbon sequestration and its role in the global carbon cycle. Geophysical Monograph Series. Washington, DC, USA: American Geophysical Union. p. 317–324.
- CARPENTER, S. R., AND C. FOLKE. 2006. Ecology for transformation. *Trends in Ecology and Evolution* 21:309–315.
- [CCSP] CLIMATE CHANGE SCIENCE PROGRAM. 2008. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. *In*: S. H. Julius and J. M. West [EDS.] and J. S. Baron, L. A. Joyce, P. Kareiva, B. D. Keller, M. A. Palmer, C. H. Peterson, and J. M. Scott [AUTHORS]. Washington, DC, USA: US Environmental Protection Agency. 873 p.
- CHAPIN, F. S., III, G. P. KOFINAS, AND C. FOLKE [EDS.]. 2009. Principles of ecosystem stewardship. Resilience-based natural resource management in a changing world. New York, NY, USA: Springer. 402 p.
- CHAPIN, F. S., III, S. R. CARPENTER, G. P. KOFINAS, C. FOLKE, N. ABEL, W. C. CLARK, P. OLSSON, D. M. STAFFORD SMITH, B. WALKER, O. R. YOUNG, F. BERKES, R. BIGGS, J. M. GROVE, R. L. NAYLOR, E. PINKERTON, W. STEPHEN, AND F. J. SWANSON. 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology and Evolution* 25:241–249.
- CHICAGO CLIMATE EXCHANGE, 2009. Chicago Climate Exchange Office Project Protocol. Agricultural Best Management Practices—Sustainably Managed Rangeland Soil Carbon Sequestration Offset Projects. 72 p. Available at: [https://www.theice.com/publicdocs/ccx/protocols/CCX\\_Protocol\\_Sustainably\\_Managed\\_Rangeland\\_Soil.pdf](https://www.theice.com/publicdocs/ccx/protocols/CCX_Protocol_Sustainably_Managed_Rangeland_Soil.pdf). Accessed 31 March 2013.
- CLEARY, M. B., E. PENDALL, AND B. E. EWERS. 2010. Aboveground and belowground carbon pools after fire in Mountain Big Sagebrush steppe. *Rangeland Ecology & Management* 63:178–196.
- COPPOCK, D. L. 2011. Ranching and multiyear droughts in Utah: production impacts, risk perceptions, and changes in preparedness. *Rangeland Ecology & Management* 64:607–618.
- CRAINE, J. M., A. J. ELMORE, K. C. OLSON, AND D. TOLLESON. 2010. Climate change and cattle nutritional stress. *Global Change Biology* 16:2901–2911.
- DAI, X., T. W. BOUTTON, M. HALEMICHAEL, R. J. ANSLEY, AND K. E. JESSUP. 2006. Soil carbon and nitrogen storage in response to fire in a temperate mixed-grass savanna. *Journal of Environmental Quality* 35:1620–1628.
- DALE, V. D., K. L. KLINE, L. L. WRIGHT, R. D. PERLACK, M. DOWNING, AND R. L. GRAHAM. 2011. Interactions among bioenergy feedstock choices, landscape dynamics, and land use. *Ecological Applications* 21:1039–1054.
- DERNER, J. D., AND G. E. SCHUMAN. 2007. Carbon sequestration and rangelands: a synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation* 62:77–85.
- DERNER, J. D., T. W. BOUTTON, AND D. D. BRISKE. 2006. Grazing and ecosystem carbon storage in the North American Great Plains. *Plant and Soil* 280:77–90.
- DESSAI, S., M. HULME, R. LEMPERT, AND R. PIELKE, JR. 2009. Climate prediction: a limit to adaptation? *In*: W. N. Adger, I. Lorenzoni, and K. L. O'Brien [EDS.]. Adapting to climate change: thresholds, values and governance. New York, NY, USA: Cambridge University Press. p. 64–78.
- DE STEIGUER, J. E. 2008. Semiarid rangelands and carbon offset markets: a look at the economic prospects. *Rangelands* 30(2):27–32.
- DE VRIES, M., AND I. J. M. DE BOER. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science* 128:1–11.
- DICKERSON, G. E. 1978. Animal size and efficiency: basic concepts. *Animal Production* 27:367–379.
- DILLING, L., AND M. C. LEMOS. 2011. Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change* 21:680–689.
- D'ODORICO, P., A. BHATTACHAN, K. F. DAVIS, S. RAVI, AND C. W. RUNYAN. 2013. Global desertification: drivers and feedbacks. *Advances in Water Research* 51:326–344.
- EAKIN, H., E. L. TOMPKINS, D. R. NELSON, AND J. M. ANDERIES. 2009. Hidden costs and disparate uncertainties: trade-offs in approaches to climate policy. *In*: W. N. Adger, I. Lorenzoni, and K. L. O'Brien [EDS.]. Adapting to climate change: thresholds, values and governance. New York, NY, USA: Cambridge University Press. p. 212–226.
- FAZEY, I., J. B. P. GAMARRA, J. FISCHER, M. S. REED, L. C. STRINGER, AND M. CHRISTIE. 2010. Adaptation strategies for reducing vulnerability to future environmental change. *Frontiers in Ecology and Environment* 8:414–422.
- FINNVEDEN, G., M. Z. HAUSCHILD, T. EKVALL, J. GUINEE, R. HEIJUNGS, S. HELLWEG, A. KOEHLER, D. PENNINGTON, AND S. SUH. 2009. Recent developments in life cycle assessment. *Journal of Environmental Management* 91:1–21.
- FOLKE, C., S. R. CARPENTER, B. WALKER, M. SCHEFFER, T. CHAPIN, AND J. ROCKSTROM. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society* 15(4):20. Available at: <http://www.ecologyandsociety.org/vol15/iss4/art20/>. Accessed 31 March 2013.
- FOLLETT, R. F., J. M. KIMBLE, AND R. LAL. 2001. The potential of U.S. grazing lands to sequester soil carbon. *In*: R. F. Follett, J. M. Kimble, and R. Lal [EDS.]. The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. Boca Raton, FL, USA: CRC Press. p. 401–430.
- FOX, W. E., D. W. MCCOLLUM, J. E. MITCHELL, L. E. SWANSON, U. P. KREUTER, J. A. TANAKA, H. T. HEINTZ, JR., R. P. BRECKENRIDGE, AND P. H. GEISSLER. 2009. Integrated social, economic and ecological conceptual framework for considering rangeland sustainability. *Society and Natural Resources* 22:593–606.
- GLIMP, H. A. 1995. Meat goat production and marketing. *Journal of Animal Science* 73:291–295.
- GUAN, H., K. M. WITTENBERG, K. H. OMINSKI, AND D. O. KRAUSE. 2006. Efficacy of ionophores in cattle diets for mitigation of enteric methane. *Journal of Animal Science* 84:1896–1906.
- GUNDERSON, L. H., S. R. CARPENTER, C. FOLKE, P. OLSSON, AND G. PETERSON. 2006. Water RATs (resilience, adaptability, and transformability) in lake and wetland social-ecological systems. *Ecology and Society* 11(1):16 Available at: <http://www.ecologyandsociety.org/vol11/iss1/art16/>. Accessed 31 March 2013.
- HAVSTAD, K. M., D. C. PETERS, R. SKAGGS, J. BROWN, B. BESTELMEYER, E. FREDRICKSON, J. HERRICK, AND J. WRIGHT. 2007. Ecological services to and from rangelands of the United States. *Ecological Economics* 64:261–268.
- HELLER, N. E., AND E. S. ZAVALA. 2008. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation* 142:14–32.
- HOFMANN, R. R., AND D. R. M. STEWART. 1972. Grazer or browser: a classification based on the stomach structure and feeding habits of East African ruminants. *Mammalia* 36:226–240.
- HOFFMANN, I. 2010. Climate change and the characterization, breeding and conservation of animal genetic resources. *Animal Genetics* 41(Suppl. 1):32–46.
- HUGHES, R. F., S. R. ARCHER, G. P. ASNER, C. A. WESSMAN, C. MCMURTRY, J. NELSON, AND R. J. ANSLEY. 2006. Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant encroachment in a temperate savanna. *Global Change Biology* 12:1733–1747.
- [IPCC] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson [EDS.]. Cambridge, UK: Cambridge University Press. 881 p.
- [IPCC] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2007a. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R. K. Pachauri, and A. Reisinger [EDS.]. Geneva, Switzerland: IPCC. 104 p. Available at: [http://www.ipcc.ch/publications\\_and\\_data/publications\\_ipcc\\_fourth\\_assessment\\_report\\_synthesis\\_report.htm](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm). Accessed 31 March 2013.
- [IPCC] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2007b. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer [EDS.]. Cambridge, UK: Cambridge University Press. 851 p.
- [IPCC] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley [EDS.]. Cambridge, UK, and New York, NY, USA: Cambridge University Press. 582 p.



- IZAURRE, R. C., J. A. MORGAN, A. M. THOMPSON, P. A. FAY, H. W. POLLEY, AND J. L. HATHFIELD. 2011. Climate impacts on agriculture: implications for forage and rangeland production. *Agronomy Journal* 103:371–381.
- JACKSON, R. B., J. L. BANNER, E. G. JOBBÁGY, W. T. POCKMAN, AND D. H. WALL. 2002. Ecosystem carbon loss with woody plant invasion of grasslands. *Nature* 418:623–626.
- JOHNSON, K. A., AND D. E. JOHNSON. 1995. Methane emissions from cattle. *Journal of Animal Science* 73:2483–2492.
- JOYCE, L. A., G. M. BLATE, J. S. LITTELL, S. G. McNULTY, C. I. MILLAR, S. C. MOSER, R. P. NEILSON, K. O'HALLORAN, AND D. L. PETERSON. 2008. National forests. In: S. H. Julius and J. M. West [EDS.] and J. S. Baron, B. Griffith, L. A. Joyce, P. Kareiva, B. D. Keller, M. A. Palmer, C. H. Peterson, and J. M. Scott [AUTHORS]. Preliminary review of adaptation options for climate-sensitive ecosystems and resources: a report by the US Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC, USA: US Environmental Protection Agency. p. 19–84.
- JOYCE L. A., G. M. BLATE, J. S. LITTELL, S. G. McNULTY, C. I. MILLAR, S. C. MOSER, R. P. NEILSON, AND D. L. PETERSON. 2009. Managing for multiple resources under a changing climate. *Environmental Management* 44:1022–1032.
- KARL, T. R., J. M. MELILLO, AND T. C. PETERSON [EDS.]. 2009. Global climate change impacts in the United States. New York, NY, USA: Cambridge University Press. 188 p.
- KATES, R. W., W. R. TRAVIS, AND T. J. WILBANKS. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences U. S. A.* 109:7156–7161.
- KAY, R. M. B. 1997. Responses of African livestock and wild herbivores to drought. *Journal of Arid Environments* 37:683–694.
- KIM, M.-K., AND B. A. McCARL. 2009. Uncertainty discounting for land-based carbon sequestration. *Journal of Agricultural and Applied Economics* 41:1–11.
- KIM, M.-K., B. A. McCARL, AND B. C. MURRAY. 2008. Permanence discounting for land-based carbon sequestration. *Ecological Economics* 64:763–769.
- KINZIG, A. P., P. RYAN, M. ETIENNE, H. ALLISON, T. ELMOVIST, AND B. H. WALKER. 2006. Resilience and regime shifts: assessing cascading effects. *Ecology and Society* 11(1):20. Available at: <http://www.ecologyandsociety.org/vol11/iss1/art20/>. Accessed 31 March 2013.
- KNAPP, C. N., AND M. E. FERNANDEZ-GIMENEZ. 2009. Knowledge in practice: documenting rancher local knowledge in northwest Colorado. *Rangeland Ecology & Management* 62:500–509.
- KOCH, R. M., M. E. DIKEMAN, AND J. D. CROUSE. 1982. Characterization of biological types of cattle (Cycle III). III. Carcass composition, quality and palatability. *Journal of Animal Science* 54:35–45.
- KREUTER, U. P., W. E. FOX, J. A. TANAKA, K. A. MACZKO, D. W. MCCOLLUM, J. E. MITCHELL, C. S. DUKE, AND L. HIDINGER. 2012. Framework for comparing ecosystem impacts of developing unconventional energy resources on western US rangelands. *Rangeland Ecology & Management* 65:433–443.
- KULSHRESHTHA, S. N. 2011. Climate change, prairie agriculture, and prairie economy: the new normal. *Canadian Journal of Agricultural Economics* 59:19–44.
- LAL, R., J. M. KIMBLE, R. F. FOLLETT, AND C. V. COLE. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Chelsea, MI, USA: Ann Arbor Press. 128 p.
- LENTON, T. M., H. HELD, E. KRIEGLER, J. W. HALL, W. LUCHT, S. RAHMSTORF, AND H. J. SCHELLHUBER. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences U. S. A.* 105:1786–1793.
- LIEBIG, M. A., J. R. GROSS, S. L. KRONBERG, R. L. PHILLIPS, AND J. D. HANSON. 2010. Grazing management contributions to net global warming potential: a long-term evaluation in the northern Great Plains. *Journal of Environmental Quality* 39:799–809.
- LOKUPITIYA, E., AND K. PAUSTIAN. 2006. Agricultural soil greenhouse gas emissions: a review of national inventory methods. *Journal of Environmental Quality* 35:1413–1427.
- MACDONALD, J., AND W. McBRIDE. 2009. The transformation of U.S. livestock agriculture: scale efficiency and risks. USDA Economic Research Service Economic Information Bulletin NO EIB-43. Available at: <http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib43.aspx>. Accessed 31 March 2013.
- MARSHALL, N. A. 2010. Understanding social resilience to climate variability in primary enterprises and industries. *Global Environmental Change* 20:36–43.
- MARSHALL, N. A., I. J. GORDON, AND A. J. ASH. 2011. The reluctance of resource-users to adopt seasonal climate forecast to enhance resilience to climate variability on the rangelands. *Climatic Change* 107:511–529.
- MARSHALL, N. A., AND A. SMAJGL. 2013. Understanding variability in adaptive capacity on rangelands. *Rangeland Ecology & Management* 66:88–94.
- MARTENS, D. A., W. EMMERICH, J. E. T. McLAIN, AND T. N. JOHNSEN. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil and Tillage Research* 83:95–119.
- MARTIN, R. E., G. P. ASNER, J. ANSLEY, AND A. R. MOSIER. 2003. Effects of woody vegetation encroachment on soil nitrogen oxide emissions in a temperate savanna. *Ecological Applications* 13:897–910.
- MARX, S. M., E. U. WEBER, B. S. ORLOVE, A. LEISEROWITZ, D. H. KRANTZ, C. RONCOLI, AND J. PHILLIPS. 2007. Communication and mental processes: experiential and analytic processing of uncertain climate information. *Global Environmental Change* 17:47–58.
- McBRIDE, W. D., AND K. MATTHEWS, JR. 2011. The diverse structure and organization of U.S. beef cow-calf farms. USDA Economic Research Service No. EIB 73. Available at: <http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib73.aspx>. Accessed 26 March 2013.
- McCARL, B. A. 2007. Adaptation options for agriculture, forestry and fisheries. A Report to the UNFCCC Secretariat Financial and Technical Support Division. Available at: [http://unfccc.int/files/cooperation\\_and\\_support/financial\\_mechanism/application/pdf/mccarl.pdf](http://unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/mccarl.pdf). Accessed 31 March 2013.
- McCARL, B. A. 2011. Agriculture. In: J. Schmandt, G. R. North, and J. Clarkson [EDS.] The impact of global warming on Texas. 2nd ed. Austin, TX, USA: University of Texas Press. p. 157–171.
- McCARL, B. A., AND U. A. SCHNEIDER. 2000. U.S. agriculture's role in a greenhouse gas emission mitigation world: an economic perspective. *Review of Agricultural Economics* 22:134–159.
- McCARL, B. A., AND U. A. SCHNEIDER. 2001. Greenhouse gas mitigation in U.S. agriculture and forestry. *Science* 294:2481–2482.
- McCARRON, J. K., A. K. KNAPP, AND J. M. BLAIR. 2003. Soil C and N responses to woody plant expansion in a mesic grassland. *Plant and Soil* 257:183–192.
- [MEA] MILLENNIUM ECOSYSTEM ASSESSMENT. 2005. Ecosystems and human well-being. Washington, DC, USA: Island Press. 917 p.
- MEINKE, H., S. M. HOWDEN, P. C. STRUIK, R. NELSON, D. RODRIGUEZ, AND S. C. CHAPMAN. 2009. Adaptation science for agriculture and natural resource management—urgency and theoretical basis. *Current Opinion in Environmental Sustainability* 1:69–76.
- MILCHUNAS, D. G., AND W. K. LAUENROTH. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecological Monographs* 63:327–366.
- MILLAR, C. I., N. L. STEPHENSON, AND S. L. STEPHENS. 2007. Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications* 17:2145–2151.
- MILLS, E. 2012. The greening of insurance. *Science* 338:1424–1425.
- MORGAN, J. A., J. D. DERNER, D. G. MILCHUNAS, AND E. PENDALL. 2008. Management implications of global change for Great Plains rangelands. *Rangelands* 30(3):18–22.
- MORGAN, J. A., R. F. FOLLETT, L. H. ALLEN, JR., S. DEL GROSSO, J. D. DERNER, F. DIJKSTRA, A. FRANZLUEBBERS, R. FRY, K. PAUSTIAN, AND M. M. SCHOENEBERGER. 2010. Carbon sequestration in agricultural lands of the United States. *Journal of Soil and Water Conservation* 65:6A–13A.
- MOSER, S. C., AND J. A. EKSTROM. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences U. S. A.* 107:22026–22031.
- MU, J. E., B. A. McCARL, AND A. M. WEIN. 2013. Adaptation to climate change: changes in farmland use and stocking rate in the U.S. *Mitigation and Adaptation of Strategies for Global Change* 18:713–730.
- NELSON, D. R., W. N. ADGER, AND K. BROWN. 2007. Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources* 32:395–419.
- [NRC] NATIONAL RESEARCH COUNCIL, AMERICA'S CLIMATE CHOICES, PANEL ON ADAPTING TO THE IMPACTS OF CLIMATE CHANGE. 2010. Adapting to Climate Change. Washington, DC, USA: National Academy Press. 290 p.

- O'NEILL, C. J., D. L. SWAIN, AND H. N. KADARMIDEEN. 2010. Evolutionary process of *Bos taurus* cattle in favourable versus unfavourable environments and its implications for genetic selection. *Evolutionary Applications* 3:422–433.
- O'REAGAIN, P. O., J. BUSHELL, C. HOLLOWAY, AND A. REID. 2009. Managing for rainfall variability: effect of grazing strategy on cattle production in a dry tropical savanna. *Animal Production Science* 49:85–99.
- O'REAGAIN, P. O., J. BUSHELL, AND B. HOLMES. 2011. Managing for rainfall variability: long-term profitability of different grazing strategies in a northern Australian tropical savanna. *Animal Production Science* 51:210–224.
- OSTERBLOM, H., M. SISENWINNE, D. SYMES, M. DADIN, T. DAW, AND C. FOLKE. 2011. Incentives, social-ecological feedbacks and European fisheries. *Marine Policy* 35:568–574.
- OWENSBY, C. E., E. F. SMITH, AND K. L. ANDERSON. 1973. Deferred rotation grazing with steers in the Kansas Flint Hills. *Journal of Range Management* 26:393–396.
- PACALA, S., AND R. SOCOLOW. 2004. Stabilization wedges: solving the climate problems for the next 50 years with existing technologies. *Science* 305:968–972.
- PARK, S. E., N. A. MARSHALL, E. JAKKU, A. M. DOWD, S. M. HOWDEN, E. MENDHAM, AND A. FLEMING. 2012. Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change* 22:115–126.
- PEEL, D. 2013. Will the cows come home? *New Mexico Stockman* 79(1):49–55.
- PELLING, M. 2011. *Adaptation to climate change: from resilience to transformation*. New York, NY, USA: Routledge Taylor and Francis Group. 224 p.
- PETERSON, D. L., C. I. MILLAR, L. A. JOYCE, M. J. FURNISS, J. E. HALOFSKY, R. P. NEILSON, AND T. L. MORELLI. 2011. Responding to climate change in national forests: a guidebook for developing adaptation options. Portland, OR, USA: USDA Forest Service Pacific Northwest Station. General Technical Report PNWGTR-855. 109 p.
- POLLEY, H. W., D. D. BRISKE, J. A. MORGAN, K. WOLTER, D. W. BAILEY, AND J. R. BROWN. 2013. Climate change and North American rangelands: evidence, trends, and implications. *Rangeland Ecology & Management* 66:493–511.
- POLLEY, H. W., A. B. FRANK, J. SANABRIA, AND R. L. PHILLIPS. 2008. Interannual variability in carbon dioxide fluxes and flux-climate relationships on grazed and ungrazed northern mixed-grass prairie. *Global Change Biology* 14:1620–1632.
- POLLEY, H. W., J. A. MORGAN, B. D. CAMPBELL, AND M. STAFFORD SMITH. 2000. Crop ecosystem responses to climatic change: rangelands. In: K. R. Reddy and H. F. Hodges [EDS.]. *Climate change and global crop productivity*. Wallingford, UK: CABI. p. 293–314.
- POPP, A., S. DOMPTAIL, N. BLAUM, AND F. JELTSCH. 2009. Landuse experience does qualify for adaptation to climate change. *Ecological Modelling* 220:694–702.
- PRESTON, B. L., R. M. WESTAWAY, AND E. J. YUEN. 2011. Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. *Mitigation and Adaptation Strategies for Global Change* 16:407–438.
- PRUETT, J. H. 2002. Immunological intervention for the control of ectoparasites—a review. *Journal of Veterinary Parasitology* 16:1–10.
- RAU, B. M., R. TAUSCH, A. REINER, D. W. JOHNSON. 2010. Influence of prescribed fire on ecosystem biomass, carbon, and nitrogen in a pinyon juniper woodland. *Rangeland Ecology & Management* 63:197–202.
- REEVES, M. C., AND J. E. MITCHELL. 2012. A synoptic review of U.S. rangelands: a technical document supporting the Forest Service 2010 RPA Assessment. Fort Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. Gen. Tech. Rep. RMRS-GTR-288. 128 p.
- REILLY, J. M., F. TUBIELLO, B. A. MCCARL, D. G. ABLER, R. DARWIN, K. FUGLIE, S. E. HOLLINGER, R. C. IZARRALDE, S. JAGTAP, J. W. JONES, L. O. MEARNES, D. S. OJIMA, E. A. PAUL, K. PAUSTIAN, S. J. RIHA, N. J. ROSENBERG, AND C. ROSENZWEIG. 2002. US agriculture and climate change: new results. *Climatic Change* 57:43–69.
- REYNOLDS, J. F., AND D. M. STAFFORD SMITH. 2002. Do humans cause deserts? In: J. F. Reynolds and D. M. Stafford Smith [EDS.]. *Dahlem Workshop Report 88*. Berlin, Germany: Dahlem University Press. p. 23–40.
- REYNOLDS, J. F., D. M. STAFFORD SMITH, E. F. LAMBIN, B. L. TURNER, II, M. MORTIMORE, S. P. BATTERBURY, T. E. DOWNING, H. DOWLATABADI, R. J. FERNÁNDEZ, J. E. HERRICK, E. HUBER-SANNWALD, H. JIANG, R. LEEEMANS, T. LYNAM, F. T. MAESTRE, M. AYARZA, AND B. WALKER. 2007. Global desertification: building a science for drylands. *Science* 316:847–851.
- RITTEN, J. P., C. T. BASTIAN, AND B. S. RASHFORD. 2012. Profitability of carbon sequestration in western rangelands of the United States. *Rangeland Ecology & Management* 65:340–350.
- RYAN, M. G., S. R. ARCHER, R. A. BIRDSEY, C. N. DAHM, L. S. HEATH, J. A. HICKE, D. Y. HOLLINGER, T. E. HUXMAN, G. S. OKIN, R. OREN, J. T. RANDERSON, AND W. H. SCHLESINGER. 2008. Land resources. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC, USA: USDA. 362 p.
- SAFI, A. S., W. J. SMITH, JR., AND Z. LIU. 2012. Rural Nevada and climate change: vulnerability, beliefs and risk perception. *Risk Analysis* 32:1041–1059.
- SAYRE, N. F., L. CARLISLE, L. HUNTSINGER, G. FISHER, AND A. SHATTUCK. 2012. The role of rangelands in diversified farming systems: innovations, obstacles, and opportunities in the USA. *Ecology and Society* 17:43. Available at: <http://dx.doi.org/10.5751/ES-04790-170443>. Accessed 6 August 2013.
- SCASTA, J. D., D. M. ENGLE, J. L. TALLEY, J. R. WEIR, J. C. STANSBERRY, S. D. FUHLENDORF, AND R. N. HARR. 2012. Pyric-herbivory to manage horn flies (Diptera: Muscidae) on cattle. *Southwestern Entomologist* 37:325–334.
- SCHUMAN, G. E., J. E. HERRICK, AND H. H. JANZEN. 2001. The dynamics of soil carbon in rangeland. In: R. F. Follett, J. M. Kimble, and R. Lal [EDS.]. *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect*. Boca Raton, FL, USA: Lewis Publishers. p. 267–290.
- SCHUMAN, G. E., H. H. JANZEN, AND J. E. HERRICK. 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 116:391–396.
- SCHUMAN, G. E., J. D. REEDER, J. T. MANLEY, R. H. HART, AND W. A. MANLEY. 1999. Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. *Ecological Applications* 9:65–71.
- SEO, S. N., B. A. MCCARL, AND R. MENDELSON. 2010. From beef cattle to sheep under global warming? An analysis of adaptation by livestock species choice in South America. *Ecological Economics* 69:2486–2494.
- SEO, S. N., AND R. MENDELSON. 2008. Animal husbandry in Africa: climate change impacts and adaptations. *African Journal of Agricultural and Resource Economics* 2:65–82.
- SMITH, G. A., B. A. MCCARL, C. S. LI, J. H. REYNOLDS, R. HAMMERSCHLAG, R. L. SASS, W. J. PARTON, S. M. OGLE, K. PAUSTIAN, J. A. HOLTkamp, AND W. BARBOUR. 2007. Harnessing farms and forests in the low-carbon economy: how to create, measure, and verify greenhouse gas offsets. In: Z. Willey and B. Chameides [EDS.]. *Harnessing farms and forests in the low-carbon economy*. Durham, NC, USA: Duke University Press. 229 p.
- SOLAIMAN, S. 2007. Assessment of the meat goat industry and future outlook for U.S. small farms. Tuskegee University. Available at: [http://www.agmrc.org/media/cms/USGoatProductionFinal\\_E1367962C32D1.pdf](http://www.agmrc.org/media/cms/USGoatProductionFinal_E1367962C32D1.pdf). Accessed 7 August 2013.
- STAFFORD SMITH, D. M., L. HORROCKS, A. HARVEY, AND C. HAMILTON. 2011. Rethinking adaptation for a 4°C World. *Philosophical Transactions of the Royal Society A* 369:196–216.
- STAFFORD SMITH, D. M., G. M. MCKEON, I. W. WATSON, B. K. HENRY, G. S. STONE, W. B. HALL, AND S. M. HOWDEN. 2007. Learning from episodes of degradation and recovery in variable Australian rangelands. *Proceedings of the National Academy of Sciences U. S. A.* 104:20690–20695.
- SVEJCAR, T., R. ANGELL, J. A. BRADFORD, W. DUGAS, W. EMMERICH, A. B. FRANK, T. GILMANOV, M. HAFAERKAMP, D. A. JOHNSON, H. MAYEUX, P. MIELNICK, J. MORGAN, N. Z. SALIENDRA, G. E. SCHUMAN, P. L. SIMS, AND K. SNYDER. 2008. Carbon fluxes on North American rangelands. *Rangeland Ecology & Management* 61:465–474.
- THORPE, J., S. A. WOLFE, AND B. HOUSTON. 2008. Potential impacts of climate change on grazing capacity of native grasslands in the Canadian prairies. *Canadian Journal of Soil Science* 88:595–609.
- THUROW, T. L., AND C. A. TAYLOR. 1999. Viewpoint: the role of drought in range management. *Journal of Range Management* 52:413–419.
- TILMAN, D., K. G. CASSMAN, P. A. MATSON, R. NAYLOR, AND S. POLASKY. 2002. Agricultural sustainability and intensive production practices. *Nature* 418:671–677.
- TORELL, L. A., S. MURUGAN, AND O. A. RAMIREZ. 2010. Economics of flexible versus conservative stocking strategies to manage climate variability risk. *Rangeland Ecology & Management* 63:415–425.
- TORELL, L. A., N. R. RIMBEY, O. A. RAMIREZ, AND D. W. MCCOLLUM. 2005. Income earning potential versus consumptive amenities in determining ranchland values. *Journal of Agricultural and Resource Economics* 30(3):537–560.
- USDA FOREST SERVICE. 2012. *Future of America's forests and rangelands: 2010 Resources Planning Act Assessment*. Washington, DC, USA: USDA Forest Service Washington Office. General Technical Report WO-87. 198 p.

- US EPA. 2012. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010. EPA 430-R-12-001 (April 2012). 481 p. Available at: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>. Accessed 31 March 2013.
- US WHITE HOUSE. 2009. Federal Leadership in Environmental, Energy, and Economic Performance. Federal Register Vol. 74, No. 194. Available at: <http://www.gpo.gov/fdsys/pkg/FR-2009-10-08/pdf/E9-24518.pdf>. Accessed 6 August 2013.
- WALKER, B., AND D. SALT. 2012. Resilience practice: building capacity to absorb disturbance and maintain function. Washington, DC, USA: Island Press. 226 p.
- WALKER, B., C. S. HOLLING, S. R. CARPENTER, AND A. KINZIG. 2004. Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society* 9(2):5. Available at: <http://www.ecologyandsociety.org/vol9/iss2/art5/>.
- WALTHALL, C. L., J. HATFIELD, P. BACKLUND, L. LENGNICK, E. MARSHALL, M. WALSH, S. ADKINS, M. AILLERY, E. A. AINSWORTH, C. AMMANN, C. J. ANDERSON, I. BARTOMEUS, L. H. BAUMGARD, F. BOOKER, B. BRADLEY, D. M. BLUMENTHAL, J. BUNCE, K. BURKEY, S. M. DABNEY, J. A. DELGADO, J. DUKES, A. FUNK, K. GARRETT, M. GLENN, D. A. GRANTZ, D. GOODRICH, S. HU, R. C. IZAURRALDE, R. A. C. JONES, S-H. KIM, A. D. B. LEAKY, K. LEWERS, T. L. MADER, A. MCCLUNG, J. MORGAN, D. J. MUTH, M. NEARING, D. M. OOSTERHUIS, D. ORT, C. PARMESAN, W. T. PETTIGREW, W. POLLEY, R. RADER, C. RICE, M. RIVINGTON, E. ROSSKOPF, W. A. SALAS, L. E. SOLLENBERGER, R. SRYGLEY, C. STÖCKLE, E. S. TAKLE, D. TIMLIN, J. W. WHITE, R. WINFREE, L. WRIGHT-MORTON, AND L. H. ZISKA. 2012. Climate change and agriculture in the United States: effects and adaptation. Washington, DC, USA: USDA. USDA Technical Bulletin 1935. 186 p. Available at: [http://www.usda.gov/oce/climate\\_change/effects.htm](http://www.usda.gov/oce/climate_change/effects.htm). Accessed 31 March 2013.
- WEST, T. O., AND J. SIX. 2007. Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. *Climatic Change* 80:25–41.
- YUEN, E., S. STONE JOVICICH, AND B. L. PRESTON. 2013. Climate change vulnerability assessments as catalysts for social learning: four case studies in south-eastern Australia. *Mitigation and Adaptation Strategies for Global Change* 18:567–590.
- ZHANG, W., A. D. HAGERMAN, AND B. A. MCCARL. 2013. How climate factors influence the spatial distribution of Texas cattle breeds. *Climatic Change* 118:183–195.
- ZILVERBERG, C. J., P. JOHNSON, J. WEINHEIMER, AND V. G. ALLEN. 2011. Energy and carbon costs of selected cow–calf systems. *Rangeland Ecology & Management* 64:573–584.
- ZISKA, L. H., D. M. BLUMENTHAL, G. B. RUNION, E. R. HUNT, JR., AND H. DIAZ-SOLTERO. 2011. Invasive species and climate change: an agronomic perspective. *Climatic Change* 105:13–42.